THE
OBSERVATORY

A REVIEW OF ASTRONOMY

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MEETING OF THE ROYAL ASTRONOMICAL SOCIETY

Friday 2025 October 10 at $16^{h}\,00^{m}$
in the Geological Society Lecture Theatre, Burlington House

Mike Lockwood, *President*
in the Chair

The President. This is a hybrid meeting. Questions can be asked during the lecture if they are put in the Q & A. Pam Rowell will read them out. Our first speaker is Professor Debora Sijacki. The title of her talk is 'The emergence of black holes at cosmic dawn'. She is a Professor at the Institute of Astronomy, Cambridge, and Deputy Director of the Kavli Institute, Cambridge. She completed her PhD at the Max Planck Institute for Astrophysics in Germany, graduating *summa cum laude*, and she was awarded a prestigious fellowship at the Institute of Astronomy, Cambridge, followed by a Hubble fellowship at the Center for Astrophysics, Harvard. Her research aims to develop realistic numerical models of the Universe which capture the formation and growth of cosmic structures with an unprecedented level of realism. She pioneered the field of supermassive black holes in cosmological simulations and demonstrated that black holes must be understood to extract exact cosmology from diverse observational methods. Her work highlights the role of high-performance computing (HPC) in cosmology and astrophysics. She has been awarded 330 million CPU-core hours on major supercomputers in the UK, EU, and USA. She received the Otto Hahn Medal and the ERC starting grant and in 2019 the Ada Lovelace Award for her outstanding contributions to and impact on HPC.

Professor Debora Sijacki. I would like to tell you about supermassive black holes and our current understanding of them, with a particular focus on the very early Universe, and to describe the new frontier we are entering as we begin to discover and study these black holes.

Black holes are some of the most exciting and enigmatic objects we know of. They lie at the intersection of mathematics, physics, and astronomy. The image from NASA shows the glow of matter as it circulates around a black hole [see Fig. 1]. What we see in this innermost region, just before the darkness at the very centre, is the last few photons orbiting the black hole that can still reach us. You have probably heard that black holes can form at the end of the evolution of massive stars. We think that stars with masses greater than about $25\,M_{\odot}$ end their lives as stellar-mass black holes.

There is a huge range of black-hole masses in our Universe, and black holes are likely the most compact objects known. In addition to stellar-mass black holes, we know of objects called supermassive black holes, with masses greater than $10^{6}\,M_{\odot}$. There is also an intriguing population in between, the so-called intermediate-mass black holes. We have several candidates and compelling theoretical arguments for why they should exist, and I will later explain why a Nobel Prize was awarded for work related to this area.

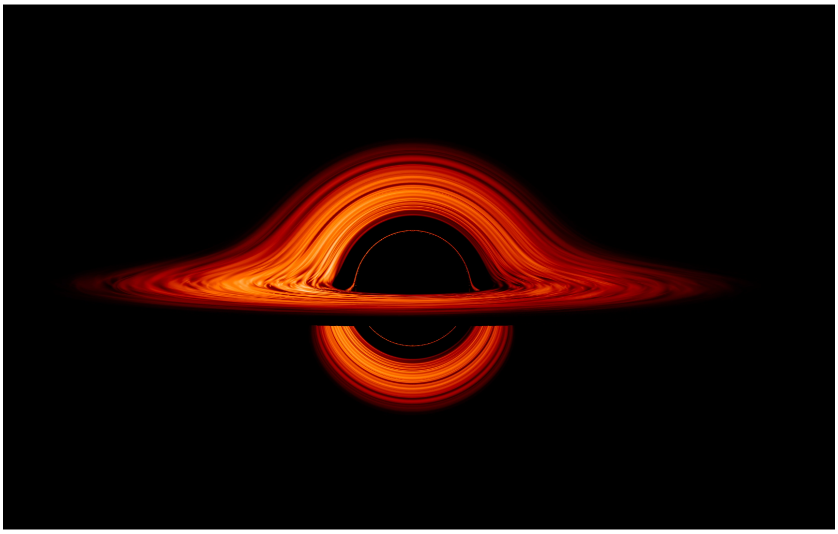

FIG. 1

Still from video at `https://svs.gsfc.nasa.gov/13326/` showing the glow of matter as it circulates around a black hole (see text). Credit: NASA's Goddard Space Flight Center/Jeremy Schnittman.

I want to explain why I believe we are in the golden age of black-hole science. The story begins with two Nobel Prizes. The first was awarded for the most precise measurement of a black hole's mass, specifically, the one at the centre of the Milky Way. Two independent teams painstakingly measured the orbits of stars very close to our Galaxy's central black hole. From the stellar orbits, and using Kepler's laws, one can deduce the mass of the central object. The mass is so large, and the object so compact, that it can only be a black hole.

Another major breakthrough in the study of stellar-mass black holes comes from gravitational-wave astronomy. The sensitivity of current detectors is high enough to detect gravitational waves produced when two stellar-mass black holes orbit and merge. Remarkably, the remnants of some of these mergers lie in the intermediate-mass–black-hole regime.

There is also extremely puzzling evidence concerning supermassive black holes. We now believe that they reside at the centres of most, if not all, galaxies. Moreover, there appears to be a fundamental link between black-hole properties, such as their mass, and key properties of their host galaxies, such as bulge mass or velocity dispersion. It is striking that although supermassive black holes are extremely compact, they seem to 'know' about the properties of the entire galaxies they inhabit. To understand how this link is established, we run large-scale cosmological simulations that model the key physical processes governing galaxy formation and evolution.

In the animation I am showing you, as the simulation of a representative sample of the Universe progresses, black holes at the centres of galaxies accrete significant amounts of matter, releasing copious energy and radiation. We believe this process regulates the supply of gas onto the black holes and ultimately sets the fundamental relation between black holes and their host galaxies.

To understand this process in more detail, we need to travel further back in time to study how galaxies and black holes assembled in the very early Universe, where our theories can be stress-tested. This is precisely where *JWST* comes in, allowing us to look much farther back in time than previously possible. We hope that *JWST* will reveal how the first black

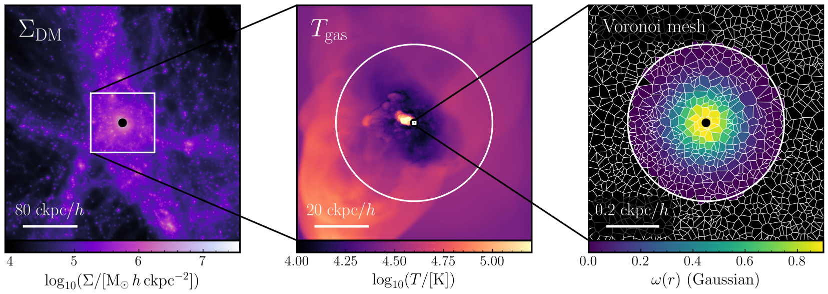

FIG. 2

Cosmological zoom-in simulation of a dwarf galaxy hosting an intermediate-mass black hole. From left to right, the panels show the dark-matter–surface-density map on large scales, the gas-temperature map (with the white circle indicating the virial radius), and the Voronoi-mesh discretization around the accreting black hole. The scale unit is *comoving* kpc/h. Adapted from Ortame *et al*., in prep.

holes formed and grew.

The Cambridge team has already made two spectacular discoveries regarding the black holes detected by *JWST*. One involves a particularly peculiar galaxy, GN-z11, which hosted a massive black hole when the Universe was only about 3% of its current age. This surprising discovery has forced theorists to revise models in an attempt to explain it. Another intriguing object from the BlackThunder collaboration in Cambridge is a massive black hole in a tiny, compact galaxy. This black hole appears to be as massive as its host galaxy, or possibly even more massive. This is extremely puzzling, because we previously assumed that galaxies formed first, yet now it is unclear how such black holes could assemble so early in the Universe's history.

We are now finding a population of very massive black holes at high redshift that no longer appear to correlate with the properties of their host galaxies. They represent a significant fraction of the host galaxy's mass. This represents a paradigm shift, and we do not yet understand how these objects formed.

One of the pioneers of black-hole studies is Lord Martin Rees; among many achievements, he produced a foundational diagram outlining how black holes may have formed in the early Universe, showing many possible pathways. We still do not know which of these pathways is most likely to produce massive black holes. Our best hope is to use new theoretical models together with *JWST* observations to solve this puzzle.

How can we learn the physics that underpins these high-redshift black holes? We have several on-going projects. In the early Universe, we are now beginning to see low-mass galaxies hosting black holes. My PhD student, Giulia Ortame, has been developing a new approach: she is studying the elusive population of intermediate-mass black holes in dwarf galaxies and exploring how *JWST* can reveal how these black holes grow over time [see Fig. 2].

Warm gas surrounds these dwarf galaxies, and this gas is heated by the powerful energy release from the central black holes. Giulia is accurately measuring the accretion rates at which matter falls into the black holes, and her findings are tantalizing. There seem to be two distinct evolutionary pathways. In one pathway, the black hole does not grow very much, and the galaxy remains in a steady state for long periods of cosmic time, forming stars slowly and continuously. The other pathway is much more dramatic: the black hole grows rapidly, expelling large amounts of gas from the tiny galaxy and causing its star formation to shut down quickly [see Fig. 3]. Giulia has shown that these two pathways likely lead to two different outcomes, one producing black holes consistent with the local scaling relation, and the other producing likely progenitors of the high-redshift black holes observed by *JWST*.

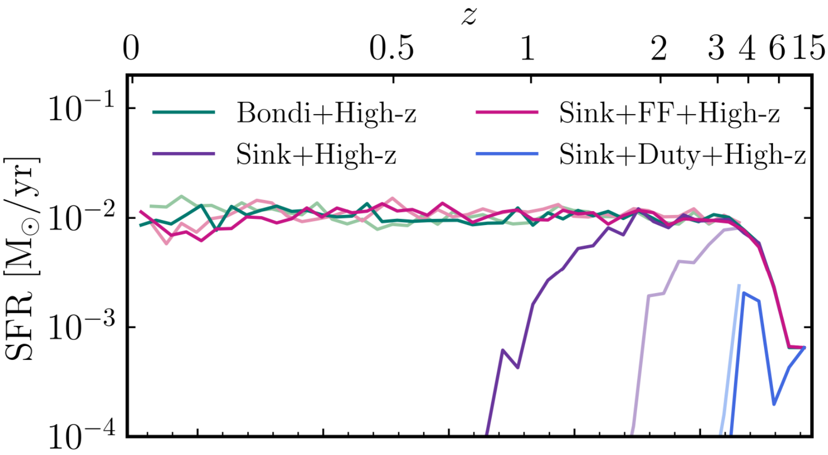

Fig. 3

The star-formation rate as a function of cosmic time for models in which the central black hole does not grow rapidly, resulting in roughly constant star formation for $z < 3$, as well as for models that allow efficient black-hole growth, which leads to rapid star-formation shutdown and dwarf-galaxy quenching (blue and purple curves). Adapted from Ortame *et al*., in prep.

Another way to study these issues is to take a representative volume of the Universe and populate it with many black holes, an approach recently adopted by Sophie Koudmani. We want to explore both different black-hole seed masses at early cosmic times and the various ways in which these black holes may grow and influence their host galaxies. Excitingly, Sophie has shown that if you start with light black-hole seeds (around a hundred $M_\odot$), it is impossible, even with very generous prescriptions for their growth, to reproduce the *JWST* population of high-redshift black holes.

Furthermore, studying high-redshift quasars is extremely helpful for breaking the degeneracy between black-hole seed masses and their accretion histories. These quasars are powered by some of the most massive black holes known and provide some of the strongest constraints on theoretical models of black-hole growth over cosmic time. At $z \sim 6$, roughly one billion years after the Universe formed, the black-hole masses are already very large, between 10^9 and 10^{10} $M_\odot$. The only way we have found in simulations to grow these 'gargantuan' black holes is to seed them extremely early in the Universe, which is consistent with *JWST* findings, and to allow them to grow very efficiently [see Fig. 4]. However, for this scenario to work, they most likely need to exceed the Eddington limit, but only for brief periods of time [see Fig. 5].

If we now believe that there is a population of very massive black holes at high redshifts, are there any other ways to test these theories and check whether they make sense? One exciting and complementary approach is to study the gravitational-wave background. This is another remarkable discovery made within the last year or so: the detection of a gravitational-wave background that we believe is most likely produced by mergers of supermassive black holes throughout the history of the Universe. One of my PhD students, Stephanie Buttigieg, has been analysing the data and finds that standard simulations are in rough agreement with the signal, although slightly low. However, when the population of *JWST* black holes is

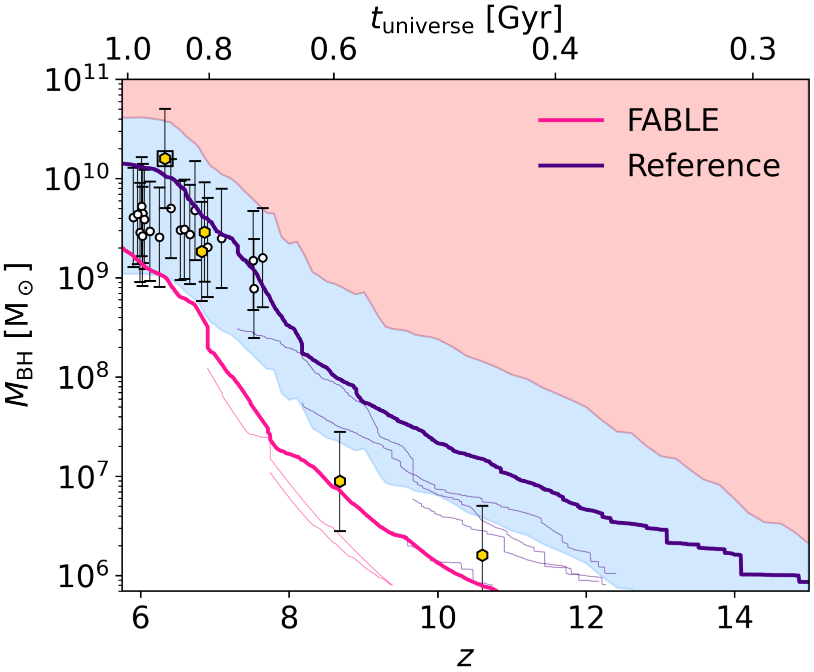

Fig. 4

Cosmological zoom-in simulation of a high-redshift protocluster hosting a bright quasar showing the growth of black-hole mass as a function of redshift for the most massive black hole in each simulation. Thinner lines indicate the mass growth of black holes that merge into the primary progenitor. Individual points represent observational black-hole measurements. Allowing for super-Eddington accretion enables black-hole growth that matches both the highest-redshift observed black holess and the brightest known high-redshift quasar. For further details on the FABLE simulation project see `https://www.kicc.cam.ac.uk/projects/fable`. Adapted from Bennett *et al.*, *MNRAS*, **527**, 1033, 2024.

included, the simulations can easily reproduce the observed signal.

Another promising and independent approach comes from cosmological probes. We know that galaxy groups and clusters are powerful cosmological tools. Recently, the major X-ray mission *eROSITA* found a deficit of gas in galaxy groups, which is highly puzzling. It may indicate that massive outflows driven by accreting black holes in these systems can push gas out of the groups. Such AGN jets can displace matter not only within groups and clusters but also much farther out. This has significant cosmological implications, especially as we aim to constrain the matter distribution in the Universe.

What does the future hold for this research area? We are fortunate to have many observational programmes on the horizon. The *ELT* will probe the formation sites of stars in the high-redshift galaxies that *JWST* is now revealing. We also have the *SKA*, which will hopefully detect numerous AGN jets and provide a new perspective on the accretion process onto black holes. And of course, we will have *LISA*, a space-borne mission designed to detect gravitational waves from merging black holes out to very high redshifts. The synergy between these different probes, combined with the latest theoretical advancements, promises to be truly transformative.

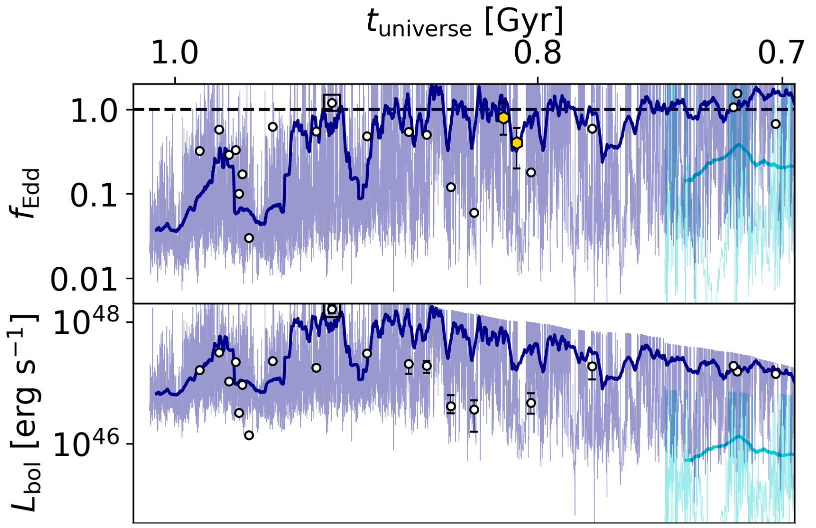

Fig. 5

The Eddington fraction (top row) and bolometric luminosity (bottom row) for the most massive black hole and its largest progenitor. Faded lines denote values at every time-step while darker lines indicate a rolling mean with a width of 100 time-steps. Observational data points are shown as open circles or gold hexagons (the latter representing *JWST* data), with uncertainties where available. The dashed horizontal line marks the Eddington limit. By modelling super-Eddington accretion, it is possible to explain the luminosities of very bright, high-redshift quasars. Adapted from Bennett *et al*., *MNRAS*, **527**, 1033, 2024.

The President. I have to say that is something rather comforting that even with all those CPU hours available, when something gets difficult you go back to pen and paper. Do we have any questions for Debora?

Reverend Garth Barber. Does this evidence for early supermassive black holes indicate an age problem in the early Universe, in other words, are we getting the age at a certain redshift wrong?

Professor Sijacki. That is a very good question. Of course, it is very exciting — there was a lot of buzz and excitement when these black holes started to be discovered at high z. Fortunately, or unfortunately, we have sufficient astrophysical uncertainty in the formation and assembly of these black holes that by Occam's Razor there is currently no pressing need to invoke alternative cosmological models before we understand the astrophysics.

Dr. Pamela Rowden. I have a question from Ian Robson who asks "How well can you determine the mass of the *JWST* very high-z supermassive black holes?"

Professor Sijacki. This is again another thing that is very much debated currently and obviously these measurements are not easy. You have to be very careful. There are different groups that made the measurements so they give some solidity in that there is independent verification. One of the objects I showed you has a different type of measurement which is much more direct, rather than entirely relying on interpreting broadened spectral lines, which gives us more confidence about these black-hole masses. A consensus is growing that at least a subset of the population should be black holes and should be quite massive, which is really exciting.

Professor Richard Ellis. It has been suggested that some of the black holes are surrounded by dense gas and the broadening that we use for the kinematics of black holes to estimate masses is only part of the explanation and the scattering of radiation can make quite a big contribution, so do you believe some of the population of black-hole masses have been overestimated because it's assumed it's all kinematics?

Professor Sijacki. I think that with some of the earlier results one has to be quite careful about them. Again, I do not think that you revise all the results. There have been a couple of papers that show that the scattering cannot explain all *JWST* results — you cannot get away with removing a black hole entirely, and in some cases black-hole masses seem robust. There will be more observations and deeper data from *JWST*. There is a lot to deliver, so these things will be ironed out.

The President. Thank you very much. That was absolutely fascinating. [Applause.]

Our next speaker is Dr. Rob Eyles-Ferris. Rob is a Research Associate at the University of Leicester who works on high-energy transients to understand the largest explosions in the Universe. His particular research interests include tidal-disruption events, fast X-ray transients, and gamma-ray bursts.

Dr. Rob Eyles-Ferris. The *Einstein Probe* (*EP*) is a new and truly innovative mission dedicated to high-energy astrophysical transients and is redefining the landscape of its field. Its revolutionary *Wide-field X-ray Telescope* (*WXT*) takes inspiration from nature, specifically the eyes of lobsters and certain other crustaceans which use tiny pores in their surface to focus light onto the retina. *WXT* uses similar micropore (or microchannel) optics to focus X-ray photons into a cross-shaped PSF. While such 'lobster-eye' instruments are less sensitive than traditional Wolter X-ray telescopes, they offer two advantages: a much lower mass and, most importantly, a far wider field of view. With twelve individual modules, *WXT* has an unprecedented field of view of 3600 square degrees in the soft (0·5–4 keV) regime and has the largest grasp (sensitivity × FoV) of any X-ray telescope.

EP/*WXT* is transforming our view of X-ray transients, in particular, fast X-ray transients (FXTs). These are short bursts of X-rays lasting hundreds to thousands of seconds, previously identifiable only in archival data long after the transient. However, *WXT* is now finding these sources in real time and, for the first time, allowing prompt follow-up and identification of the systems that power these objects. While some have been linked to previously known classes of transient, such as long gamma-ray bursts (LGRBs), many have more unique origins.

EP250108a, detected in 2025 January, is one such FXT. The initial burst of X-rays lasted 2·5 ksec before rapidly fading beyond the reach of even the most sensitive X-ray telescopes. However, I used the 2-m *Liverpool Telescope* to find its much longer-lived optical counterpart. This source exhibited unusual properties, being much bluer (hotter) than expected for an LGRB counterpart, for instance. The counterpart faded and cooled quickly before rising again as a type-Ic broad-lined (Ic-BL) supernova. These supernovae are caused by the collapse of massive stars and are often observed following LGRBs, suggesting a common origin between these transients and EP250108a. Our extensive observing campaign, which included ground- and space-based telescopes from the *Very Large Telescope* in Chile to *JWST*, produced a wealth of data across the electromagnetic spectrum through which we could unravel the mysterious nature of EP250108a. [See Fig. 6].

There are two ways a collapsing star could produce the X-rays seen in EP250108a, through a convective engine or through launching a narrow jet of ejecta. Both engines accelerate material to speeds close to the speed of light but the mass required to produce the observed luminosity differs significantly with convective engines requiring significantly greater mass. The first phase of EP250108a's optical counterpart, which we dubbed the 'fast-cooling phase', is consistent with explosive ejecta expanding at speeds a few tenths the speed of light, and that provides a clue as to how the FXT is powered. For the material to have slowed to the measured speeds by the time of the optical detection, a relatively low mass is required pointing towards the jet engine. However, these jets, which also power LGRBs, normally produce much redder 'afterglow' emission and long-lived X-ray and radio counterparts, none of which is seen in EP250108a. Instead, we suggest the jet was trapped either within the

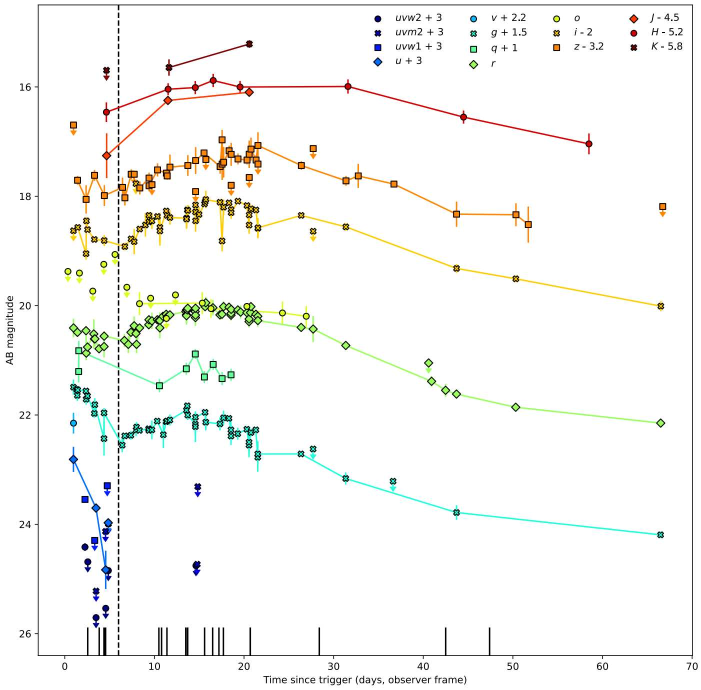

Fig. 6

The light-curve of EP250108a's counterpart across UV, optical, and infrared bands (bottom to top). The dashed vertical line indicates the cutoff between the fast-cooling phase and the rising Ic-BL supernova. The black vertical lines indicate our spectroscopic observations.

outer layers of the star or in the dense environment surrounding it to form a cocoon. These rarely observed cocoons produce blue optical emission as they rapidly expand, exactly as we saw in EP250108a. [see Fig. 7].

The later supernova provides further clues as to EP250108a's nature. It closely resembles Ic-BLs associated with LGRBs and other FXTs suggesting the same type of star powers all these transients. This is consistent with our progenitor analysis which points towards a Wolf–Rayet star 15 to 30 times the mass of the Sun. Our detailed spectra reveal further hints as to the environment of the star. In particular, we see both evidence of hydrogen and helium in the spectra. One particular hydrogen feature only briefly appears suggesting it could be evidence of an extended shell, while helium is detected by *JWST* but not in optical spectra. Together, these point towards a complex environment with significant earlier mass loss from the star, possibly through stellar winds or common-envelope ejection, and implies EP250108a's progenitor probably resided in a binary or possibly even triple system.

There are still a number of open questions in the case of EP250108a. The exact reason the jet failed to break out is still unknown — was the jet inherently weaker than typical for this type of stellar collapse or was it trapped due to an exceptionally dense and complex environment? The picture has been further complicated by *EP*'s detection of three more FXTs linked to Ic-BLs. In one case, EP240414a, a third red component was observed pointing towards a jet that just breaks out, while the other two sources display their own unique properties. Together this suggests there is a spectrum to the jet behaviour that we are only just starting

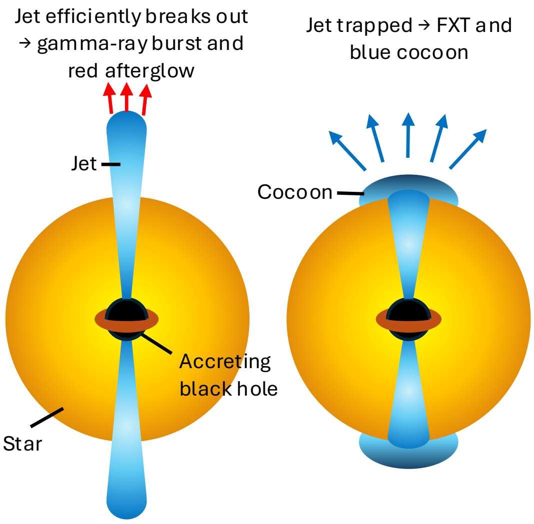

Fig. 7

The difference between LGRBs and FXTs with cocoons like EP250108a. On the left, the jet efficiently breaks out to produce the LGRB and an afterglow. The right hand-side shows the situation in EP250108a where the jet is unable to break out and instead forms the blue thermal cocoon.

to uncover thanks to *EP*. Future detections will be vital for answering these questions and determining exactly how the deaths of massive stars power these extreme events.

The President. Thank you very much. We have a question on-line.

Dr. Rowell. A question from an anonymous attendee: “What percentage of the mass–energy accreting onto BHs gets ejected in the jets? (I presume all jets are equal and opposite to conserve momentum.)”

Dr. Eyles-Ferris. Jet physics is very complicated. We are still not entirely sure how they work and I very much simplified the picture here. You don’t always get just jets, you sometimes get outflows which are moving much more slowly but at much wider angles. Again we are not really sure how they happen or whether they occur in a core-collapse supernova. There is quite a lot of debate as to exactly what is going on. We don’t know for sure how much mass is ejected. It is most of it, I think.

Professor Paul Crowther. Can you say anything about the size of the progenitor — was it a compact WR thing or a giant?

Dr. Eyles-Ferris. We presume it was a Wolf–Rayet probably with its atmosphere stripped. It seems a fairly typical supernova progenitor for a GRB.

Professor Crowther. Yes, along the lines of a typical SN Ic, broad-lined with a compact, hot, WR-like He-rich envelope.

Dr. Eyles-Ferris. Yes.

The President. Thank you very much. [Applause.] Before I introduce the next speaker I must tell you a story. When ChatGPT first arrived, my colleague Chris Scott decided to take my magnetohydrodynamics lectures and ask them to be re-written in the style of Monty Python. [Laughter.] Unfortunately, he didn’t notice any difference, so he then asked them to be written in the style of the Goons. What is interesting is that it was identifiably my notes, it was identifiably the Goon Show, but after you got over the amusement of Bluebottle talking about magnetic reconnection, it was profoundly unfunny. Our next speaker is Niall Jeffrey from University College London. The reason I told you that story is because the title of his talk is 'What has AI ever done for us: learning about dark energy from dark matter'. Niall did his PhD at UCL in 2019 and then went to Paris at the École Normale Supérieure and he is currently a Senior Research Fellow back at UCL.

Dr. Niall Jeffrey. Understanding the cosmological model and the nature of the dark sector — dark matter and dark energy — remains one of the central challenges in fundamental physics. About 95% of the mass–energy content of the Universe is attributed to these components, yet their properties and physical origin are unknown.

Recent results from the *DESI* experiment suggest that dark energy could be a dynamic and exotic form of matter–energy rather than Einstein's cosmological constant, as previously thought.

The European Space Agency's *Euclid* mission, launched in 2023, and the *Rubin Observatory* Legacy Survey of Space and Time (LSST) are upcoming cosmological experiments designed to produce decisive constraints on dark-energy models. Among their primary probes is weak gravitational lensing, which traces the distribution of dark matter and provides a powerful test of dark-energy physics through its effect on cosmic structure.

Using new techniques from Artificial Intelligence (AI) within a rigorous statistical framework, we can unlock new signatures of dark energy in these data. This will allow us to discover or rule out different models of dark energy that would otherwise remain indistinguishable.

In advance of data from this new generation of cosmological experiments, current surveys have taken the lead in developing these methods. One such experiment is the Dark Energy Survey (DES) — an international collaboration to map hundreds of millions of galaxies. Using the gravitational-lensing effect, these data are used to trace the dark-matter distribution in the Universe.

Our team in DES has developed and applied a new AI framework, simulation-based inference (SBI), to analyse weak-lensing data and to measure dark energy with unprecedented precision. SBI is a novel technique that answers scientifically rigorous statistical questions, using AI as a mathematical tool to do so. In this sense, the results are both testable and interpretable — this is not 'black-box' AI.

In DES, SBI uses realistic simulations of the Universe to perform statistical inference directly on the data, without relying on statistical approximations (regarding the 'likelihood' of data) or relying on simplified summary statistics (*e.g.*, power spectra). Instead, with SBI we learn from simulated data that include observational realism, enabling information from the full lensing maps to be used in the inference. In this way, we use SBI to provide realism, so that we trust our results, which then means we can reliably extract more information from our data directly from the dark-matter maps.

This 'map-level' inference substantially improved the constraining power of DES. Applied to gravitational-lensing data, SBI has delivered the most precise dark-energy analysis to date, improving dark-energy constraints by more than a factor of two — equivalent to quadrupling the effective DES data volume.

These analyses were enabled by the Gower Street simulation suite, comprising nearly 5000 large-volume cosmological simulations spanning three dark-energy models. These simulations were produced using the UK's scientific supercomputing infrastructure, *DiRAC*. Developed for DES and extended for *Euclid*, this suite incorporates noise, masks, redshift uncertainties, and galaxy alignments. SBI then connects these simulated data and the 'true' cosmological model (used in the simulated universe) using techniques from probabilistic AI. Introducing the actual observed data to these learned statistical models leads to posterior probabilities on the cosmological parameters of our Universe.

The techniques established with DES are now being extended to *Euclid*, whose imaging data and survey volume will far exceed those of DES. By integrating SBI with *Euclid* analyses, we will obtain the most accurate and precise inference of dark energy from weak gravitational lensing.

If we want to exploit these ground-breaking data sets even further, we can use more of the *Euclid* data that probe relatively small cosmological scales (separations of roughly 5 Mpc).

This can introduce new challenges, as it requires simulations at increasingly small scales, where they become computationally expensive. However, new statistical machine-learning techniques motivated by this cosmological challenge are already being developed — and they promise to transform how we learn the physics of the dark Universe.

The President. Thank you very much, Niall. Do we have any questions?

Reverend Barber. You started by saying that using AI you build trust. How can you be sure that you are not baking in prejudice in your assumptions when you are training the AI?

Dr. Jeffrey. There are two different answers to that, one of which is in the AI system. Is it finding the optimal solution that we think it is? Has it converged? We have a statistical test to do that. I think that maybe what your question was about is whether the models that you are feeding the simulation are somehow wrong: there are assumptions going in that the AI system is using and are somehow wrong. I get this question after almost every talk and the answer is the same for all of science. Every time the Dark Energy Survey or the *Large Hadron Collider* does an analysis we have solutions and we are expected to be more clear about our assumptions. We do lay them out better than other analysts do. There is the usual problem of known unknowns and we can try and check if there are sources of systematic error there. There is a problem with unknown unknowns but that is not a problem for AI or this kind of analysis — that is a problem for anyone who has ever done a scientific analysis. Actually, because of the speed of this kind of thing we are able to do tests that people who are not using these tests are not able to do — goodness-of-fits — so it actually adds an extra layer of trust at the end as well.

The President. Actually I had a similar question. I was wondering if there was any advantage in going back to what we knew before AI discovery and then feeding it all through and seeing what it makes when we know we have missed something out.

Dr. Jeffrey. When these simulation-based inference techniques first came out, people did exactly that. They ran the pipeline through SN data, for example, to see if they recovered the discovery of dark energy and they got exactly the same error bars. For older results, no one trusts this at the moment, so for any analysis we have to re-do it on old theories and every single time it works.

The President. It is always the worry what would AI do when faced with something that we did not know about.

Dr. Jeffrey. That is true of all science. Plots before scatter plots and then there is an outlier. It is the scientific method that is the problem there.

Professor Ellis. There is the figure on the left with the two-point correlation function and then you said the great advantage with the new method is that you can do it very much faster. It is equivalent to having better data. I'm sure that the contours have shrunk but the answer is different so why is that?

Dr. Jeffrey. Do you know the answer? [Laughter.]

Professor Ellis. It's offset.

Dr. Jeffrey. It's offset, yes. You are looking at different data, in effect. When you measure the power spectrum you are taking a fraction of the DES data. If you did any experiment twice there would be an offset because its a random process so there is noise that is in the map level that is not in the power-spectrum analysis. They are not the same data, just with a different model, it is actually new data.

Professor Ellis. That is kind of worrying, though?

Dr. Jeffrey. No. If we did an experiment and then published our results, we shouldn't get the error bars in the same place, they should be offset because we both have different data. What is happening here is that the map-level stuff is actually seeing different data than what is in the two-point, so if this was in the same place that is the worrying thing because it means we have cheated.

Professor Ellis. So the original paper is wrong?

Dr. Jeffrey. No. It is a fact that the map level is seeing information data in some way that the two-point is not seeing, so you expect there to be a shift because it is stochastic.

Dr. Patrick Leahy. I'm not a total expert on this but I know that you don't have to stop at two-point. If you go to three-point, four-point, *etc*., do you end up summarizing all the information that is in the data?

Dr. Jeffrey. Technically not. Practically, if we do it in three-point, it improves it by 20%, not a factor of two. The reason why is because you can characterize a statistical process by a sum of n-point functions only if it is somehow perturbative. As soon as you have non-linear structure formation, in this case of dark matter crossing over each other, it became more non-perturbative so you are not guaranteed that that particular expansion would converge to all the information.

Dr. Quentin Stanley. There is an interesting thing that was pointed out to me recently and this is the danger of training data that is diagnosing on cancerous moles where a lot of training data was taken from images taken over many years and grew a data set. The trouble was that the final result was determined whether or not the rule that was used to measure the mole was present in those images. Metadata is one of those unknown unknowns which is present and you do not realize it has been there. We had a presentation last year when it was looking at lots of data from datasets and trying to get the same data from datasets to match is very difficult and therefore you have this added problem of making sure your simulations match the type of data you've got. It is a huge problem and it is a magical thing to get anywhere close to it.

Dr. Jeffrey. Simulating things is hard. If we don't include something in our simulation of the active data then these contours would be in the wrong place. There is a whole other aspect of this which is standard statistics, which is goodness-of-fit testing. If I have my data, what are my parameters which have been learned, but there is also an aspect which 'is do the simulations in our case look like the observations?' and there is significant work being done on that front as well. It is things that people are not doing in the standard analysis — people don't do these goodness-of-fit things like posterior-predicted distributions, prior-predicted distributions. We are forced to do it because of questions like this. Nobody else is doing it so we are actually going significantly beyond those goodness-of-fit-metrics.

Dr. Stanley. Could you define the phrase 'looks like'?

Dr. Jeffrey. No. It's mathematically well defined. It's just difficult to convert that statement into words. Every time you have a statistical process then there is some probability distribution which is millions of dimensions. This is a higher-dimension space of images that we expect and images that we don't expect, so if we can somehow change that higher-dimension probability space you can say, given the actual data I have got, whether it was high probability.

Dr. Stanley. I know that in the world there is a huge examination of the type of statistics you can use. It can differ and again, this is part of the learning process. In 100 years it will be a totally different scene.

The President. The problem is not a new one. When neural networks were first introduced they tried to use it on aircraft identification and it was getting Russian and US aircraft right every time, until they gave it a colour photo of a Russian plane. Any other questions?

A Fellow. It seems to me that in the last ten years there have been few occasions when theoreticians have told observers that their observations are wrong. Is that anybody else's experience? ΛCDM has proved itself to be extremely flexible — there are a couple of parameters in there which can be adjusted until the theory fits the facts. Can you design experiments with your AI which will actually test the theory, but a real scientific method which is to try and invalidate the theorem.

Dr. Jeffrey. When I say information-extraction, what it is doing is designing an experiment. It is saying that two-point statistics as an experiment are less good. Can you design some other summary of the data? In terms of questions like 'Can you invalidate. . . ?', I think it comes back to this question of goodness-of-fit, and obviously as a scientist that is what we would like, which is additionally 'Can our model not in every way describe our data?' I suppose that is almost always true and then you get rid of all sources of systematic error and hopefully find that it still doesn't match. I think that is like goodness-of-fit but I don't think that design is necessarily the way to go, partly because we are not limited by our data anymore. Cosmology is not a data-limited exercise, it is a methodology, a theoretical statistics-limited problem. At the moment all the dark-energy results combine galaxy observations, CMB, and SN. With *Euclid* weak lensing alone will be able to beat down the error bar on some things. Rather than trying to think what the next step is we will have our work cut out just trying to use that dataset alone.

The President. Thank you very much. [Applause.] I'm not sure what I have learned. [Laughter.] I'm actually wondering if I should give a talk on what differential calculus can do for us. A big thank you to our speakers this evening, it has been absolutely wonderful. The next Highlights meeting will be on Friday, November 14th. We are unable to offer drinks at Burlington House today due to a mixture of licensing laws and fire-regulation problems. We are looking at it and will find an alternative solution. Thanks for coming and thank you again to our speakers and we'll see you in a month.

MEETING OF THE ROYAL ASTRONOMICAL SOCIETY

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

Mike Lockwood, *President*
in the Chair

The President. A couple of speakers were unable to make it today so we have two talks on-line and one in person. The first speaker is Nigel Meredith. Nigel started at UCL in 1984 and moved to the downland outstation at Mullard Space Science Laboratory in 1996. Since 2004 he has worked at the British Antarctic Survey in Cambridge and his work on the radiation belts won him the RAS Chapman Medal this year. He will be talking about 'Extreme relativistic electron fluxes in the Earth's outer radiation belt'.

Dr. Nigel Meredith. Relativistic electrons ($E > 0{\cdot}5$ MeV) are a major source of radiation damage to satellites. These, so-called 'killer electrons', can penetrate satellite surfaces and embed themselves in insulating materials and ungrounded conductors. Here, the charge accumulates over time, resulting in the build-up of high electric fields which may eventually exceed breakdown levels. The subsequent discharge may lead to phantom commands, logic errors, loss of functionality and, in rare cases, serious harm to a satellite.

Relativistic electrons in near-Earth space normally occupy two distinct zones. The inner radiation belt, which typically occurs in the region $1{\cdot}2 < L < 2{\cdot}0$, is relatively stable. Here L is the distance from the centre of the Earth to the magnetic equatorial crossing of a given geomagnetic field line measured in Earth radii. Further out, the outer radiation belt typically lies in region $3 < L < 8$ and is highly dynamic.

Our critical infrastructure extends to 6·6 Earth radii. As of 2023 there were over 7500 operational satellites in Earth orbit, including 6800 in low Earth orbit, 143 in medium Earth orbit, and 590 in geostationary orbit. Most are exposed to relativistic electrons in the Earth's radiation belts at some or all points in their orbits.

To determine the highest fluxes that may potentially be encountered in any given orbit we use a branch of statistics known as extreme-value analysis. For consistency with an earlier study of relativistic electrons at geostationary orbit, we use the excess-over-high-threshold method. For this approach the appropriate distribution function is the Generalized Pareto Distribution.

In 2014, we conducted an extreme-value analysis of the daily averaged $E > 2\,\mathrm{MeV}$ electron fluxes from the *GOES* satellites in geostationary orbit during the 19·5 year period from 1995 January 1 to 2014 June 30. We found the 1-in-10, 1-in-50, and 1-in-100-years daily averaged $E > 2\,\mathrm{MeV}$ electron fluxes at *GOES West* to be $1{\cdot}8 \times 10^5$, $5{\cdot}0 \times 10^5$, and $7{\cdot}7 \times 10^5\,\mathrm{cm^{-2}\,s^{-1}\,sr^{-1}}$, respectively. The largest event seen during this period was a particularly extreme event, which the extreme-value analysis suggests was a 1-in-50-years event.

More recently, we conducted an extreme-value analysis of the daily averaged electron fluxes in GPS orbit as a function of energy and L using data from the US *GPS NS41* satellite during the 19·5 year period from 2000 December 10 to 2020 July 25. We found that the 1-in-10-years flux at $L = 4{\cdot}5$, in the heart of the outer radiation belt, decreases with increasing energy ranging from $8{\cdot}2\ \times 10^6\,\mathrm{cm^{-2}\,s^{-1}\,sr^{-1}\,MeV^{-1}}$ at $E = 0{\cdot}6\,\mathrm{MeV}$ to $33\,\mathrm{cm^{-2}\,s^{-1}\,sr^{-1}\,MeV^{-1}}$ at $E = 8{\cdot}0\,\mathrm{MeV}$. In this region, the 1-in-100-years event is a factor of 1·1–1·7 times larger than the corresponding 1-in-10-years event. Further out, the 1-in-10-years flux at $L = 6{\cdot}5$, on field lines which map to the vicinity of geostationary orbit, decreases with increasing energy ranging from $6{\cdot}2^5\,\mathrm{cm^{-2}\,s^{-1}\,sr^{-1}\,MeV^{-1}}$ at $E = 0{\cdot}6\,\mathrm{MeV}$ to $0{\cdot}48\,\mathrm{cm^{-2}\,s^{-1}\,sr^{-1}\,MeV^{-1}}$ at $E = 8{\cdot}0\,\mathrm{MeV}$. Here, the 1-in-100-years event is a factor of 1·1–13 times larger than the corresponding 1-in-10-years event, with the value of the factor increasing with increasing energy.

The determination of the 1-in-10 and 1-in-100-years extreme fluxes of $E > 2\,\mathrm{MeV}$ electrons in geostationary orbit had immediate impact. They have been used by the Met Office to update the UK Cabinet Office National Security Risk Assessment and included the US 'Space Weather Phase 1 Benchmarks' report. They have also been used by SES Global, a major satellite operator, to improve the definition of spacecraft requirements and in the evaluation of satellite proposals, and by Atrium Space Insurance Consortium, a consortium of ten Lloyd's of London insurance syndicates, in dialogues with clients.

Having discussed some of my recent research, I will now spend the remainder of my talk discussing my outreach activities with the 'sounds of space'. Space is a near-perfect vacuum and utterly silent. However, space is full of a rich variety of electromagnetic and gravitational waves. Converting these waves to sound reveals series of weird and wonderful noises, known as the 'sounds of space'.

In 2017 we set up a multi-disciplinary art–science collaboration, the Sounds of Space Project, comprising musician/composer Kim Cunio, multimedia artist Diana Scarborough, and myself, to exploit these amazing natural 'sounds' and make them more accessible to wider audiences. We have since used the space 'sounds' in talks, performances (including animations, soundscapes, and contemporary dance), short films, and music.

In 2018 we started work on an album, combining 'sounds' from the VLF receiver at the Halley Research Station in the Antarctic with original music. The resulting album, *Aurora Musicalis*, was released in 2020 May. It is partly a soundscape drawn from our most mysterious continent and partly a response to the natural radio 'sounds' of our planet. It invites us to relax and enjoy the 'sounds of space' set to ambient music on the grand piano.

Our second album, *Celestial Incantations*, released in 2021 June, builds on the first album by introducing a whole new spectrum of space 'sounds' and a huge musical palette — including orchestral instruments, traditional instruments, and electronics. This album invites us to consider the vastness of space, and embark on a spectacular journey of 'sound' from Earth to beyond the Galaxy.

We have since released additional albums, exploring different themes. *Sunconscious*, released in 2022, features music inspired by and including 'sounds' of the Sun. These eclectic 'sounds' are accompanied by the hurdy-gurdy, the theremin, an electronic keyboard, and harmonic chanting into a well. More recently, *Moontopia*, released in 2025, features music inspired by and including space 'sounds' recorded by spacecraft in the vicinity of moons of Jupiter and Saturn. These 'sounds' are accompanied by a variety of instruments including the piano, percussion, keyboards, the daegum, and a didjeridoo.

In a separate venture the 'sounds of space' from Halley were incorporated into an update of the space simulation video game *Elite Dangerous* in 2018 December. In this collaboration I worked with Frontier Developments, the creators of *Elite Dangerous*, to incorporate the eerie sounds into the new gameplay.

The President. Thank you very much. Do we have any questions?

Mr. Horace Regnart. It is worth remembering that about 20% of the world's economy depends on near-Earth space activity.

Dr. Meredith. That's right.

The President. Could I ask you a question? You mentioned insurance issues. I notice that my home insurance is invalidated if I don't lock the front door when I go out. Is the same sort of thing happening in space if people, for example, power down and then leave the spacecraft. Is the insurance invalidated or is that not yet on the cards?

Dr. Meredith. I don't have access to any precise details on how our findings have been used by the insurance industry. However, I do know that they have been used by spacecraft insurers to help them make sure that satellite manufacturers and operators are doing all they can to ensure that satellites have sufficient design margins.

The President. The reason I ask it is because it raises the level of trust in the forecast.

Dr. Meredith. Space weather, like weather on Earth, can be highly variable and difficult to forecast accurately all of the time. We provide our best forecasts to our stakeholders and they use them as part of their analysis of on-going risks. As our forecasts develop and their use increases our stakeholders will be able to get a better assessment of the utility of the forecasts.

Dr. Pamela Rowden. John Fairweather comments "Those of us who remember *Journey into Space* these sounds will remind us of that programme".

Mr. Jerry Stone. I have another comment. When you played the first sounds it immediately reminded me of the *Cassini–Huygens* mission that there was a transmission showing sounds when *Cassini* passed through the plane of Saturn's rings. There was a quite remarkable sound difference when that happened.

Dr. Meredith. I've not heard those sounds. I expect they are amazing.

Mr. Stone. I have been on to YouTube to see clips of *Aurora Musicalis* and other things and I am looking to get some copies.

Dr. Meredith. The albums, together with extensive liner notes, are available on bandcamp (`https://soundsofspaceproject.bandcamp.com`). A selection of our albums are also available on the usual streaming platforms (Amazon music, Spotify, YouTube music *etc*.).

The President. I have to admit that I found some of them quite relaxing but I was worried that, as Chairman, I would fall asleep.

Dr. Meredith. I think *Aurora Musicalis* is especially relaxing. It covers 24 hours of activity at Halley Base so you can sit down and listen, and imagine that you are at Halley listening to the sounds. The 'sounds' changes as the day goes by, adding an extra dimension to the album

Dr. Paul Daniels. I am on the RAS Megaconstellation committee. Over the next decade to 15 years or so there are estimated to be 100 000 to 250 000 satellites launched into low Earth orbit which will very likely mean very serious consequences for ground-based astronomy across all wavelengths. I have heard that Space-X are planning to expand their three LEO [low-earth-orbit] satellites to include data centres distributed around the Earth in low Earth orbit. I'm concerned that there could be a serious effect on satellites raising the risk of collision by so many of them becoming non-responsive. On the other hand if we start to place too much of our computing infrastructure into orbit then it becomes vulnerable to natural events, not counting malicious actors, we may find ourselves running into problems in the future. Would you agree that that is a reasonable summary?

Dr. Meredith. I think that is a very reasonable summary. During space-weather events we get beautiful and stunning displays of the aurora which contain huge electrical currents that heat the atmosphere and cause it to expand upwards. The expansion slows down satellites and space junk and increases the risk of collision. At BAS we use radars to measure and model the effects of space weather on satellites and space junk. Putting more satellites up increases the risk of collisions as well.

The President. Thank you very much, Nigel. [Applause.] We should say that space is a very hostile place and some people would do well to remember that. Our next speaker is also on-line, Steven Cunnington, from the University of Manchester. Steven started at Jodrell Bank and then for a while he was the Stephen Hawking Fellow at the Institute of Cosmology and Gravitation at the University of Portsmouth. He is now back at Jodrell Bank, particularly because of *SKAO*. He specializes in optical- and radio-survey synergies, particularly looking for large-scale structure. The title of his talk is 'A new way to map the Universe with radio intensity maps of neutral hydrogen'.

Dr. Steven Cunnington. I am going to a new approach to studying the large-scale structure of the Universe using intensity of neutral hydrogen (H I). This method, currently being developed with the *MeerKAT* radio array in South Africa, measures the combined 21-cm emission from extragalactic H I without resolving individual galaxies, allowing cosmologists to chart the cosmic web more efficiently across much greater volumes.

I will begin by setting the cosmological context. While the CDM model successfully accounts for much of what is observed, it leaves open major questions concerning the nature of dark matter and dark energy, the origin of cosmic inflation, and the validity of general relativity on the largest scales. Persistent tensions between independent measurements, most notably of the Hubble constant, also continue to attract scepticism over the completeness of CDM.

Traditional optical surveys map structure by cataloguing millions of galaxies individually, but this approach is both observationally expensive and increasingly limited at high redshift. Intensity mapping offers an alternative: by measuring the total, unresolved 21-cm emission from neutral hydrogen across the sky and frequency, one obtains a three-dimensional map that traces the matter-density fluctuations. The technique can reach higher redshifts than optical surveys, and the radio telescopes provide an independent probe of cosmology with different systematics. Furthermore, the capability to cover vast volumes spanning billions of light-years unlocks unexplored fluctuations across ultra-large scales, where evidence for new physics may be revealed. These scales are sensitive to the physics of inflation and provide unique tests of Einstein's theory of gravity.

Whilst offering great promise, the 21-cm signal from the cosmic web is, however, extremely faint compared with bright foregrounds from Galactic synchrotron emission, extragalactic radio sources, and radio-frequency interference (RFI). These challenges can be mitigated through careful calibration and statistical cross-correlation with optical galaxy surveys, which help isolate the cosmological component.

The *MeerKAT* telescope, comprising 64 dishes in the Karoo Desert, serves as a world-class observatory and a precursor to the forthcoming *SKA-Mid* array of the *Square Kilometre Array* Observatory (*SKAO*). Its key cosmological programme, *MeerKAT*'s Large Area Synoptic Survey (MeerKLASS), will map roughly 10 000 square degrees over the redshift range

$0{\cdot}4 < z < 1{\cdot}45$. Several pilot surveys in both the L-band and UHF-band have already been completed.

The unique observational strategy is crucial for accessing the largest scales. The field of view from conventional interferometric imaging, where signals from pairs of dishes are correlated, is limited by the array's minimum baseline and therefore loses sensitivity to very broad angular modes. MeerKLASS instead operates the *MeerKAT* array in single-dish mode, using each antenna independently to measure total power, with the results combined statistically. This enables sensitivity to large cosmological scales.

Recent work has demonstrated the success of this approach. From a MeerKLASS pilot survey, Cunnington *et al*. achieved a 7·7-σ detection of clustering through cross-correlation of *MeerKAT* intensity maps with overlapping optical galaxy surveys, the first detection of cosmological large-scale structure using a multi-dish radio telescope [see Fig. 1]. This marked an important milestone for 21-cm cosmology and confirms that the single-dish technique can recover the desired signal.

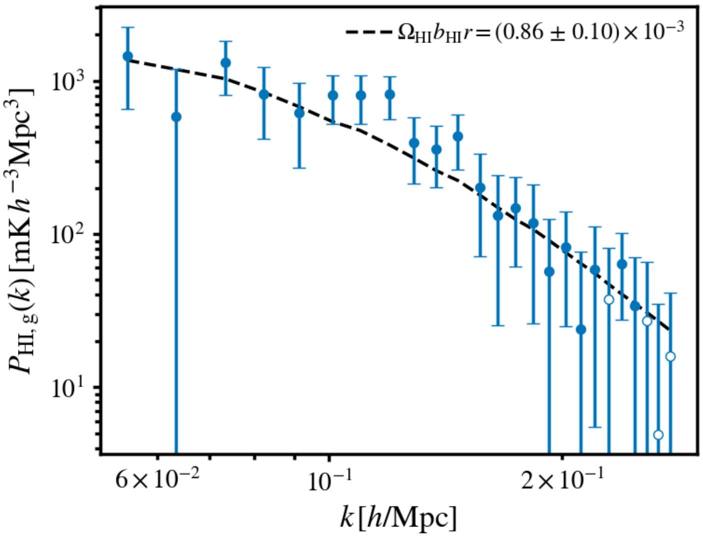

Fig. 1

7·7-σ spatial-power-spectrum-detection between the *MeerKAT* pilot 21-cm intensity map and WiggleZ galaxies at $z \approx 0{\cdot}43$ (`https://arxiv.org/abs/2206.01579` [*MNRAS*, **518**, 6262, 2023]), demonstrating a shared clustering signature between the two tracer fields (21-cm and galaxies). This validates the 21-cm intensity-mapping method on which MeerKLASS is building. Hollow markers indicate negative power. The dashed line is a theoretical model.

Deeper follow-up observations, with around four times more observing hours, further improved sensitivity and control of systematics. Consistent detections of a cosmological power spectrum with MeerKLASS are now being made, plus direct detections of an H I profile by stacking the maps onto positions of overlapping galaxies has also been demonstrated.

Owing to these successful detections, MeerKLASS is now receiving increased support and has grown to become the largest project conducted within *MeerKAT* in terms of observational resources. New observations are now underway, with a planned 2500 hours of observing time over several years. The survey has now reached nearly 3000 square degrees, already making MeerKLASS the largest-volume spectroscopic survey in the southern hemisphere, and will ultimately extend to 10 000 square degrees in the pre-*SKAO* era. Early analyses indicate that even as the survey approaches the bright Galactic plane, foreground contamination remains well controlled, reinforcing the potential for ultra-wide radio surveys with both MeerKLASS and the future *SKAO*.

In conclusion, it is clear that radio intensity mapping of neutral hydrogen is emerging as a powerful new tool for large-scale cosmology. The continuing MeerKLASS observations will refine methods and demonstrate the feasibility of precision cosmology in the radio domain, paving the way for the transformative surveys to be carried out with the *SKAO*.

The President. Thank you very much. When you mentioned using more telescopes to get more done presumably if you were using different combinations of interferometers to improve the resolution you can still get things done when you have the full array — is that true?

Dr. Cunnington. We always use the full array, but crucially do not primarily use it as an interferometer. We instead use it in single-dish mode, *i.e.*, we take the autocorrelations from each dish as it rapidly scans to give low-resolution maps but over vast sky areas very quickly. However, we are now demonstrating an ‘On The Fly’ technique whereby images can be constructed from the cross-correlations between antennas, despite the constantly moving dishes. This effectively provides a high-angular-resolution interferometric survey at no additional cost.

Professor Richard Ellis. Very exciting. In the frequency range that *MeerKat* can cover is there any possibility of intensity mapping in other spectrum lines or not?

Dr. Cunnington. Not in the region that *MeerKat* is sensitive to. *MeerKat* is pretty well centred on 21 cm. This can be seen as an advantage. Given the highly isolated 21-cm emission feature, the probability of line confusion or interlopers is very low, which is a problem for other line experiments.

The President. Thank you very much indeed. [Applause.] Now we come to the George Darwin Lecture from Dr. Dimitri Veras of the University of Warwick. Dimitri started off with his PhD at the University of Colorado, Boulder. He has worked in Florida and Cambridge, and for the past 12 years he has been at Warwick. He is going to tell us about what is a gloriously multi-science activity: looking at white-dwarf planetary systems. His talk is entitled ‘The growing, interdisciplinary field of post-main-sequence planetary-system science’.

Dr. Dimitri Veras. I would like to thank the RAS for the George Darwin Lecture. I am honoured to win it and I hope that my talk reflects that today.

The fate of planetary systems represents a growing field of study which draws from different disciplines, including stellar science, planetary science, and geophysics. Related observational campaigns and theoretical pursuits vary significantly, accommodating a wide range of expertise, and different communities are invited to contribute to this research area.

The future evolutionary path of our Sun qualitatively mirrors that of the vast majority of stars in the Milky Way, passing through giant-branch phases before becoming a white dwarf. During the giant-branch phases, the star’s resulting radius expansion, mass loss, and luminosity changes significantly alter the architecture of the orbiting planets, asteroids, comets, and dust. The radius expansion will envelope all material within a few astronomical units, the mass loss stretches out the orbits of the survivors while altering their stability boundaries, and the luminosity increase is sufficient to spin up asteroids to rotational fission on a system-wide scale.

Observations indicate that the resulting planetary system is far from quiescent. As the star becomes a white dwarf and cools down for its remaining lifetime, a combination of the gravitational interactions between planets and asteroids, the influences of stellar fly-bys and Galactic tides on exo-Oort-cloud comets, and the drag from dimming stellar radiation draw in material into the immediate vicinity of the star. This planetary material breaks up close to the white dwarf, yielding debris discs. These debris discs then accrete onto the white dwarf, whose crushingly high density breaks apart the compounds and molecules in the debris into constituent elements.

The debris, the discs, and the photospheric metals are all observable, and have represented the primary drivers for study of the field of white-dwarf planetary systems for decades. The relative abundances of the observed metals are used to reconstruct the compositions and extent of differentiation of the broken-up asteroids and comets, providing a direct glimpse into the bulk chemical composition of exo-planetesimals. The discs are eccentric, wispy, and largely transient, unlike many other astrophysical discs, and in particular unlike protoplanetary discs. Some minor planets are observed in the process of breaking up into debris, as evidenced by their dusty effluences and how the corresponding photometric light curves vary on time-scales of weeks or even days.

Much harder to observe are the major planets themselves, despite the likely pivotal role they play in shaping these systems. The small number of planets found so far have been discovered through a wide variety of techniques, and the community is actively pursuing additional discoveries through current and future facilities.

Theoretical efforts to understand the formation, evolution, and destruction of these systems as well as the individual objects within them have varied from purely analytical to purely numerical investigations. These studies have tackled a wide range of relevant questions, including: How can gravitational instability be triggered late in the life of a white dwarf? How do the orbits of minor planets circularize when reaching the close vicinity of the white dwarf? How do the white-dwarf discs evolve and what is their lifetime? Do the chemical constituents of exo-asteroids differ fundamentally from our knowledge and thinking of Solar System objects?

These questions represent one of several reasons why the research field of planetary-system fates has garnered interest in the astrophysics and geophysics communities. Another reason is that the observations are enticing and usually surprising in some manner, keeping the field fresh and well suited for both exploratory and follow-up investigations.

Professor Ellis. Truly amazing, all that data is absolutely fantastic. White dwarfs are spanning the whole age of the Milky Way. If you go to the very bottom of the cooling curve you are seeing objects that formed when the Milky Way was in its infancy and the protostellar gas clouds would presumably be chemically pristine. I would imagine that you don't have planets at that stage. Do you have material that is chemically pristine?

Dr. Veras. The older the white dwarf is, the cooler it is, the more difficult it is to observe, but we have actually found metal enrichment around white dwarfs that have cooling ages of ten billion years. That is the extreme case, the paper was published only in 2022, but there is one white dwarf with a cooling age of about nine billion years and one with ten billion years and we have seen metal enrichment there. Unfortunately with a sample size of two it is hard to obtain too many correlations but they do show some unusual traits, so we hope to find more especially with all this unpublished data.

Mr. Stewart Coulter. You said that the first exoplanet to be discovered was around a pulsar?

Dr. Veras. It was the first discovered and confirmed exoplanet.

Mr. Coulter. That is a very rare sort of planet. Was it observational bias that revealed that?

Dr. Veras. I think that Aleksander Wolszczan and Dale Frail found those planets. Alex told me that he found them using Arecibo which was undergoing maintenance so he asked the Director if he could use the telescope and he was able to get a lot of data. There was a bit of good fortune there and also we do know that they are generally quite rare: there have been dedicated studies to look for millisecond pulsars and there have been only a handful of detections since then. Those planets are also second-generation planets — any existing planets did not survive the supernova so we think that those planets re-formed from the fallback from the supernova. The first known planetary system was detected around a white dwarf in 1917 by Adriaan van Maanen. He actually saw calcium lines in the photosphere of the white dwarf. He did not understand what he was seeing and neither did we until 100 years later and in terms of firsts that is actually the first planetary system found. For completeness, before 1992, there were hints of radial-velocity exoplanets by Bruce Campbell in 1988 but he could not confirm at the time because the curves did not look very robust. That was γ Cep B and it turns out there is a planet there but it was not confirmed until much later. [The planet is γ Cep Ab, orbiting the primary. — Ed.]

The President. You are going to have everyone scurrying back to look at old journals!

Dr. Veras. I actually asked Aleksander Wolszczan about the first newspaper article reporting that so I had to do some digging myself to find that.

Miss Maria Kuznetsova. I wanted to ask you what kind of metal core do the white dwarfs have? Is it diamagnetic metals or magnetic metals such as nickel or iron? That would be an important point.

Dr. Veras. Most white dwarfs have a core of oxygen and carbon but the more massive ones can have a neon/oxygen core and in terms of the origin of the magnetic fields it could be relics but some of the white dwarfs are spinning fast enough that they generate magnetic fields.

Miss Sabiya Tamadar. When you mentioned the detection of calcium I was interested in how it was differentiated. Do you have any insights about that?

Dr. Veras. When the white dwarf is so dense it will crush any minor planet at the Roche radius. The minor planets are composed of many different metals. Calcium as a spectral line shows up very brightly in the photospheres so that is why we are able to see so much calcium there. We might be missing those other metals that are harder to see.

The President. Thank you very much Dimitri. [Applause.] We can welcome you back to Burlington House for tea. See you next month.

REDISCUSSION OF ECLIPSING BINARIES. PAPER 29: THE F-TYPE TWIN SYSTEM BS DRACONIS

By John Southworth

Astrophysics Group, Keele University, Staffordshire, ST5 5BG, UK

We present an analysis of BS Dra, a detached eclipsing binary containing two almost-identical F3 V stars in a 3·36-d circular orbit, based on 40 sectors of observations from the *Transiting Exoplanet Survey Satellite* (*TESS*) and published spectroscopic results. We measure masses of $1{\cdot}305 \pm 0{\cdot}015\,M_\odot$ and $1{\cdot}284 \pm 0{\cdot}017\,M_\odot$, and radii of $1{\cdot}409 \pm 0{\cdot}006\,R_\odot$ and $1{\cdot}400 \pm 0{\cdot}006\,R_\odot$, for the two components. The high quality of the *TESS* data allow — for the first time — a definitive identification of the primary eclipse, which is 0·007 mag deeper than the secondary. The primary star is the hotter, larger, and more massive of the two: the ratios of the radii and surface brightnesses are both slightly but significantly below unity. We find a distance concordant with the *Gaia* DR3 parallax and, by comparison to theoretical models, an age of 1600 ± 300 Myr and a slightly sub-solar chemical composition. Our mean times of primary eclipse, each representing all eclipses in one sector, have a

scatter of only 0·37 s around a linear ephemeris: BS Dra may be useful as a celestial clock.

Introduction

Detached eclipsing binaries (dEBs) are a foundational source of measurements of the physical properties of normal stars[1,2]. Their properties can be determined using only observational data, geometric models, and celestial mechanics. Photometric and spectroscopic data of high quality permit the measurement of mass and radius in 'well-behaved' dEBs to precisions of better than 0·2%[3]. The *Detached Eclipsing Binary Catalogue*[4] (*DEBCat*[*]) currently lists 367 dEBs with mass and radius measurements to approximately 2% or better, and the current series of papers[5] aims to increase this number using new photometry from space missions[6] such as *TESS*[7] and *Kepler*[8].

In this work we present an analysis of BS Draconis (Table I), which consists of two F3 V stars so similar that previous work has been unable to definitively establish which is the primary component. It is sited in the northern continuous viewing zone of *TESS* so has been extensively observed throughout its mission. Below we are able to identify with certainty which is the primary eclipse, as it is 0·007 mag deeper than the secondary eclipse. We refer to the primary component (eclipsed at primary eclipse) as star A and its companion as star B.

BS Draconis

Table I

Basic information on BS Draconis. The BV magnitudes are each the mean of 91 individual measurements[9] distributed approximately randomly in orbital phase. The JHK_s magnitudes from 2MASS[10] were obtained at an orbital phase of 0·885.

Property	*Value*	*Reference*
Right ascension (J2000)	$14^{h}22^{m}49^{s}{\cdot}698$	11
Declination (J2000)	$+14^{\circ}56'20''{\cdot}14$	11
Henry Draper designation	HD 190020	12
Hipparcos designation	HIP 98118	13
Tycho designation	TYC 4457-2347-1	9
Gaia DR3 designation	2287962824139508224	14
Gaia DR3 parallax (mas)	5·1193 ± 0·0131	14
TESS Input Catalog designation	TIC 237277760	15
B magnitude	9·638 ± 0·023	9
V magnitude	9·183 ± 0·022	9
J magnitude	8·268 ± 0·023	10
H magnitude	8·070 ± 0·017	10
K_s magnitude	8·027 ± 0·022	10
Spectral type	F3 V + F3 V	16,17

BS Dra was found to be eclipsing by Strohmeier in 1959[18,19] with a period of 1·682 d and a name of BV 241. Fitzgerald[20] obtained 19 photographic spectra with a reciprocal dispersion of 33 Å mm^{-1}, measured radial velocities (RVs), and determined minimum masses for the stars. He found the spectral lines of the two components to be of approximately equal strength, and the orbital period to be double that given by Strohmeier because the primary and secondary eclipses were practically indistinguishable.

Popper[16] obtained 17 photographic spectra of BS Dra at 16·1 Å mm^{-1}, using the Lick 120-inch (3·1-m) telescope and coudé spectrograph. Popper also gave minimum masses, but

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

not the physical properties of the system because no light-curve was available.

A good V-band light-curve of BS Dra was obtained by Popper & Dumont[21] and analysed by Popper & Etzel[22]. They found the stars to have almost identical radii and surface brightnesses, and that ratios of the radii between 0·95 and 1·05 gave nearly indistinguishable fits to the data.

Light-curves containing 476 points in each of the B and V bands, and covering most of the eclipse phases, were published by Ibanoğlu *et al.*[23] and analysed by Güdür *et al.*[24] They combined their analysis of those data with the spectroscopic results of Popper[16] to determine the properties of BS Dra for the first time. Russo *et al.*[25] reanalysed the same data with a different approach, and obtained similar results. A comparable dataset was obtained by Chis *et al.*[26], and normal points and an analysis were published by Christesen *et al.*[27]

Milone *et al.*[17] (hereafter M05) presented a measurement of the properties of the system based on light-curves in the $H_{\rm P}$, $B_{\rm T}$, and $V_{\rm T}$ bands from the *Hipparcos* satellite and medium-resolution (resolving power $R = 20\,000$) spectroscopy from the Asiago 1·82-m telescope in the region of the near-infrared calcium triplet. They estimated a spectral type of F3 V and a sub-solar metallicity of [Fe/H] $\approx -0{\cdot}4$ from comparisons with spectral atlases. The $B_{\rm T}$ and $V_{\rm T}$ light-curves were highly scattered, and the $H_{\rm P}$ photometry included only 12 data points during eclipse, so their measurements of the radii of the stars were imprecise. To the author's knowledge, no further analysis of this system has been published.

Photometric observations

BS Dra is the subject of an abundance of data from the *TESS* mission, which has been used to observe it in a total of 40 sectors. Thirty-eight of these were observed at the best (120-s) cadence, sector 41 was observed at 600-s cadence, and sector 59 at 200-s cadence. We used the LIGHTKURVE package[28] to download the SPOC (Science Processing Center[29]) light-curves for all 40 sectors from the NASA Mikulski Archive for Space Telescopes (MAST*), specifying the "hard" option to reject data flagged as lower quality.

The data were converted from flux into differential magnitudes and the median magnitude was subtracted from each sector. We then visually inspected all sectors to reject stretches of data away from fully-observed transits, ending with a total of 603 334 datapoints from the original 667 710(!) points. A representative plot from sector 83 is shown in Fig. 1.

We queried the *Gaia* DR3 database† for a list of all sources within 2 arcmin of BS Dra. This search returned 44 sources in addition to the target itself, the brightest two being 3·4 mag and 3·9 mag fainter in the $G_{\rm RP}$ band than BS Dra itself. We thus expect the amount of third light in the *TESS* data of our target to be small.

Light-curve analysis

The profusion of *TESS* data available for BS Dra demands the use of a fast modelling code for its interpretation. As the two stars are well separated, we used version 44 of the JKTEBOP‡ code[30,31]. Our analysis followed that for UZ Dra in Paper 27[32]. We fitted each *TESS* sector separately, to allow for changes in parameters such as third light. For each sector we fitted for the orbital period (P), a reference time of primary minimum (T_0) close to the midpoint of that sector, the sum ($r_{\rm A} + r_{\rm B}$) and ratio ($k = r_{\rm B}/r_{\rm A}$) of the fractional radii, the central-surface-brightness ratio (J), third light (L_3), and orbital inclination (i).

Limb darkening (LD) was allowed for using the power-2 law[33–35]. As the two stars are almost identical, we adopted the same LD coefficients for both, fitted for the linear coefficient (c) and fixed the non-linear coefficient (α) at a theoretical value[36,37]. We also fitted for

*`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`

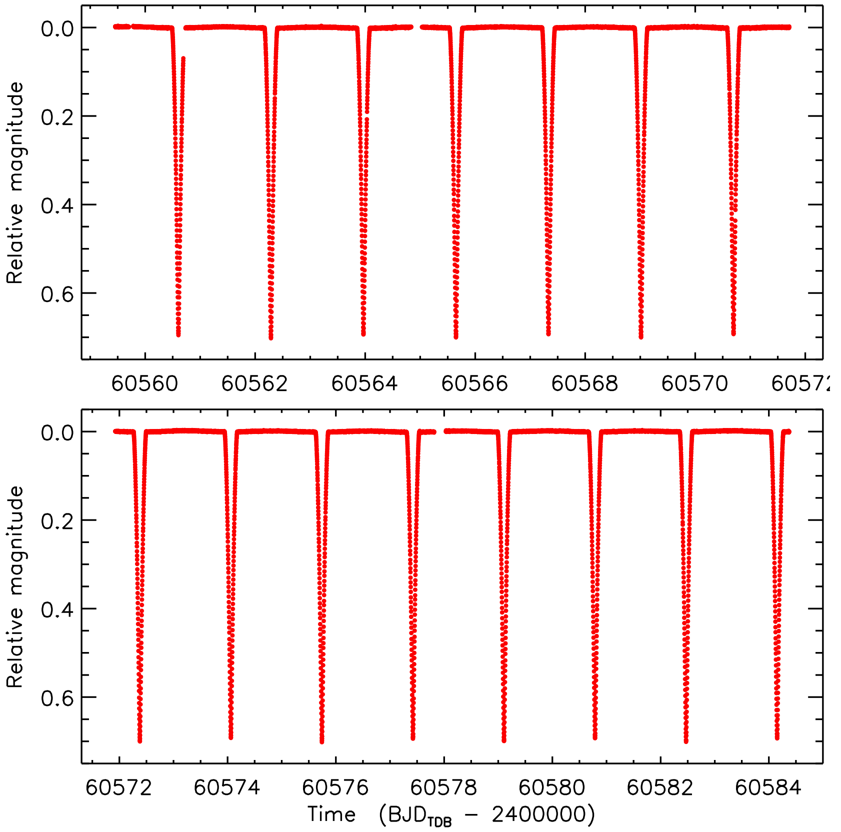

Fig. 1

Light-curve of BS Dra from *TESS* sector 83, chosen as it has very few data gaps. The flux measurements have been converted to magnitude units and the median subtracted.

several nuisance parameters: the coefficients of a straight line representing the out-of-eclipse brightness of the system for each subset of data, and the coefficients of the reflection effect for both stars. We assumed the orbit to be circular as there is no indication of eccentricity in the available data. An example fit can be found in Fig. 2.

As an experiment, we initially treated sector 41, which has a cadence of 600 s, identically to the other sectors. The results showed good agreement with the other sectors with the exception of the orbital inclination, which was lower by 0·05° (5 σ). We then accounted for the lower cadence by numerically integrating the model in the fitting process[38] and found that the results shifted to complete agreement with other sectors. Sector 59 was observed at 200-s cadence: the fitted parameters are in full agreement with other sectors even without accounting for the slightly lower sampling rate.

The final photometric parameters were calculated by taking the unweighted mean and standard deviation of the values from the individual sectors, and are given in Table II. We refrained from adopting the standard errors of the parameters because they are too small — the agreement between sectors is so good that the standard errors are significantly smaller

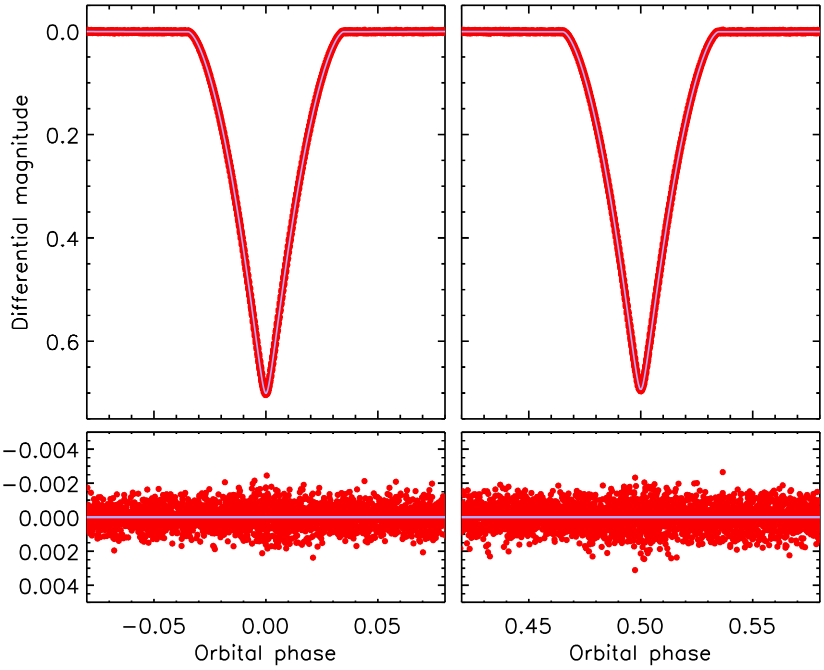

FIG. 2

JKTEBOP best fit to the light-curves of BS Dra from *TESS* sector 83 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.

than the limit to which we trust our modelling code (see ref. 3 for further information). We also calculated uncertainties for each sector using Monte Carlo (MC) simulations[39] (after scaling the data errors to give a reduced χ^2 of $\chi^2_\nu = 1$), finding that the MC error bars slightly underpredict the scatter between the parameter values for different sectors.

Fig. 3 shows the values of some of photometric parameters for each *TESS* sector. We see the same story as for UZ Dra: that the astrophysical parameters are very stable with time but third light varies slightly. This is expected because *TESS* has a coarse pixel scale and the satellite's orientation changes each sector, so background stars may drift in and out of the pixel mask used to generate the photometry of our target star. We also see that the light ratio is definitively less than unity which, combined with the small but clear difference in depth of the two eclipses in Fig. 2, means our identification of the hotter star (star A) is certain.

Orbital ephemeris

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

$$\text{Min I} = \text{BJD}_{\text{TDB}}\ 2459728{\cdot}011509(2) + 3{\cdot}364012273(4)E, \qquad (1)$$

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 $\chi^2_\nu = 2{\cdot}2$, so the uncertainties

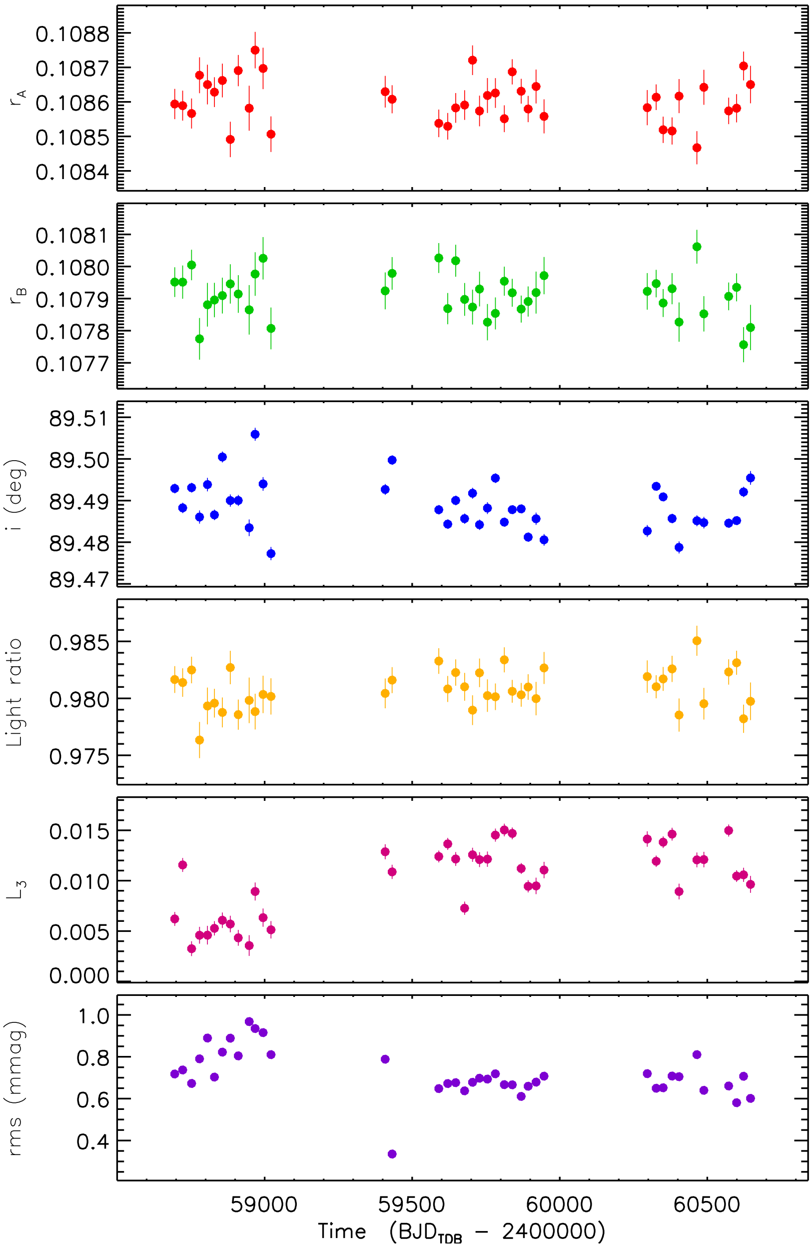

Fig. 3

The best fit to selected photometric parameters of BS Dra from all *TESS* sectors. The times used on the abscissae are given in Table III. The error bars are from the MC simulations.

TABLE II

Photometric parameters measured using JKTEBOP *from the TESS light-curves of BS Dra. The error bars are the standard deviation of the results for individual sectors.*

Parameter	*Value*
Fitted parameters:	
Orbital inclination (°)	89·487 ± 0·010
Sum of the fractional radii	0·21652 ± 0·00008
Ratio of the radii	0·9934 ± 0·0010
Central-surface-brightness ratio	0·9935 ± 0·0008
Third light	0·0099 ± 0·0036
LD coefficient c	0·602 ± 0·010
LD coefficient α	0·4984 (fixed)
Derived parameters:	
Fractional radius of star A	0·10861 ± 0·00007
Fractional radius of star B	0·10791 ± 0·00007
Light ratio $\ell_{\rm B}/\ell_{\rm A}$	0·9808 ± 0·0017

in the ephemeris have been multiplied by $\sqrt{\chi^2_\nu}$ to account for this. The r.m.s. scatter is a remarkable 0·37 s: BS Dra has deep V-shaped eclipses which are optimal for the precise determination of the time of midpoint. The individual timings are given in Table III and the residuals are plotted in Fig. 4.

TABLE III

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

Orbital cycle	*Eclipse time (BJD$_{TDB}$)*	*Uncertainty (d)*	*Residual (d)*	*TESS sector*
−307·0	2458695·259746	0·000003	0·000005	14
−299·0	2458722·171840	0·000003	0·000000	15
−290·0	2458752·447953	0·000003	0·000003	16
−282·0	2458779·360048	0·000003	−0·000000	17
−274·0	2458806·272136	0·000004	−0·000010	18
−267·0	2458829·820231	0·000003	−0·000001	19
−259·0	2458856·732334	0·000003	0·000004	20
−251·0	2458883·644433	0·000003	0·000004	21
−243·0	2458910·556525	0·000003	−0·000002	22
−232·0	2458947·560666	0·000005	0·000004	23
−226·0	2458967·744729	0·000004	−0·000006	24
−218·0	2458994·656834	0·000004	0·000000	25
−210·0	2459021·568933	0·000003	0·000001	26
−95·0	2459408·430344	0·000003	0·000001	40
−88·0	2459431·978433	0·000003	0·000004	41
−41·0	2459590·087008	0·000003	0·000002	47
−32·0	2459620·363120	0·000003	0·000004	48
−24·0	2459647·275209	0·000003	−0·000006	49
−15·0	2459677·551331	0·000003	0·000006	50
−7·0	2459704·463425	0·000003	0·000002	51
0·0	2459728·011504	0·000003	−0·000005	52
8·0	2459754·923605	0·000003	−0·000002	53
16·0	2459781·835703	0·000003	−0·000003	54
25·0	2459812·111814	0·000002	−0·000002	55
33·0	2459839·023909	0·000002	−0·000005	56
42·0	2459869·300024	0·000002	−0·000001	57

(continued on next page)

Orbital cycle	*Eclipse time (BJD_{TDB})*	*Uncertainty (d)*	*Residual (d)*	*TESS sector*
49·0	2459892·848112	0·000003	0·000001	58
57·0	2459919·760204	0·000004	−0·000005	59
65·0	2459946·672303	0·000003	−0·000004	60
169·0	2460296·529590	0·000003	0·000007	73
178·0	2460326·805698	0·000002	0·000004	74
185·0	2460350·353776	0·000002	−0·000004	75
194·0	2460380·629888	0·000003	−0·000002	76
201·0	2460404·177971	0·000003	−0·000005	77
219·0	2460464·730197	0·000003	−0·000000	79
226·0	2460488·278293	0·000003	0·000010	80
251·0	2460572·378596	0·000002	0·000006	83
259·0	2460599·290683	0·000002	−0·000005	84
266·0	2460622·838778	0·000003	0·000004	85
273·0	2460646·386858	0·000005	−0·000002	86

We also fitted quadratic and cubic functions of time to compare to the linear ephemeris, finding that they do not give an improved fit. We set a $3-\sigma$ upper limit of $9{\cdot}6 \times 10^{-11}$ s s^{-1} ($2{\cdot}0$ ms yr^{-1}) on the rate of change of orbital period. This limit could be improved if published times of minimum light were added to the analysis, but this is outside the scope of the current work.

Radial-velocity analysis

Three previous studies of BS Dra have presented RVs: Fitzgerald[20] obtained 19 coudé photographic spectra; Popper[16] observed 17 coudé photographic spectra with twice the dispersion; and M05 presented RVs from 27 échelle spectra obtained with a CCD. We have copied all the RVs from these works and refitted them using JKTEBOP to check the results (Table IV), adopting a circular orbit. The P was fixed to 3·364012273 d, and T_0 and the velocity amplitudes $K_{\rm A}$ and $K_{\rm B}$ were the fitted parameters. We used 1000 Monte Carlo simulations each to obtain uncertainties[40]. Transformation to a standard scale is not accounted for in the values or uncertainties of the systemic velocities.

The Fitzgerald RVs are provided with weights. We converted these into uncertainties and scaled them to obtain $\chi^2_\nu = 1{\cdot}0$ for the RVs for each star individually. We then obtained two fits to the RVs for the two stars: with one systemic velocity for the system (V_γ) and with separate systemic velocities for the two stars ($V_{\gamma,{\rm A}}$ and $V_{\gamma,{\rm B}}$). Our results agree with those of Fitzgerald's to within the error bars. We find a larger r.m.s. scatter, partly because we quote the value for all RVs whereas Fitzgerald's value was for RVs with unit weight.

The Popper RVs are not provided with weights so we assumed an equal uncertainty for each star: that which gave $\chi^2_\nu = 1{\cdot}0$ (see Table IV). Our identification of which is the primary star differs from Popper's so we swapped the RV data files for the two stars. Our results are in good agreement with those of Popper, including the finding of a slightly different systemic velocity for the two stars (with a significance of $1{\cdot}8\,\sigma$).

The RVs from M05 were not provided with individual uncertainties so we again assigned the same uncertainty to all RVs per star in order to obtain $\chi^2_\nu = 1{\cdot}0$. Our finding of 2·3 and 2·1km s^{-1}, for star A and star B, respectively, is much greater than the 0·19 and 0·15km s^{-1} quoted by M05 (their table 4). M05 also did not fit spectroscopic orbits but instead included their RVs with the *Hipparcos* light-curve in a global fit which directly yielded mass and radius measurements. We have calculated the equivalent $K_{\rm A}$ and $K_{\rm B}$ values and inserted them in Table IV.

The two photographic RV datasets both give values of $K_{\rm A}$ and $K_{\rm B}$ which are larger than the modern equivalents (M05 RVs) and have slight discrepancies between the systemic velocities for the two stars. Because of this, and that the M05 RVs are both more numerous

TABLE IV

Spectroscopic orbits for BS 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. The $K_{\rm A}$ and $K_{\rm B}$ values for Mo5 were calculated from other parameters given in that work. All quantities are given in km s^{-1}.

Source	$K_{\rm A}$	$K_{\rm B}$	V_γ	$V_{\gamma,{\rm A}}$	$V_{\gamma,{\rm B}}$	$\sigma_{\rm A}$	$\sigma_{\rm B}$
Fitzgerald[20]	99·4 ± 1·7	100·4 ± 1·7	+1·3 ± 1·0			2·0	2·0
This work (Fitzgerald RVs)	100·1 ± 1·1	101·1 ± 1·8		+0·4 ± 1·0	+2·3 ± 1·4	5·3	6·7
This work (Fitzgerald RVs)	100·0 ± 1·1	100·9 ± 1·8	+1·0 ± 0·8			5·2	6·7
Popper[16]	99·1 ± 0·9	99·2 ± 1·2		+2·2 ± 0·8	+0·4 ± 1·0	3·1	4·1
This work (Popper RVs)	99·3 ± 1·1	99·2 ± 0·7		+0·0 ± 1·0	+2·2 ± 0·7	3·8	2·8
This work (Popper RVs)	99·3 ± 1·2	99·2 ± 0·8	+1·6 ± 0·6			4·1	2·9
Mo5	(96·6)	(98·0)	−0·5 ± 1·5			0·19	0·15
This work (Mo5 RVs, adopted)	96·8 ± 0·6	98·4 ± 0·5		−0·6 ± 0·4	−0·5 ± 0·4	2·34	2·05
This work (Mo5 RVs)	96·8 ± 0·6	98·4 ± 0·5	−0·6 ± 0·3			2·34	2·05

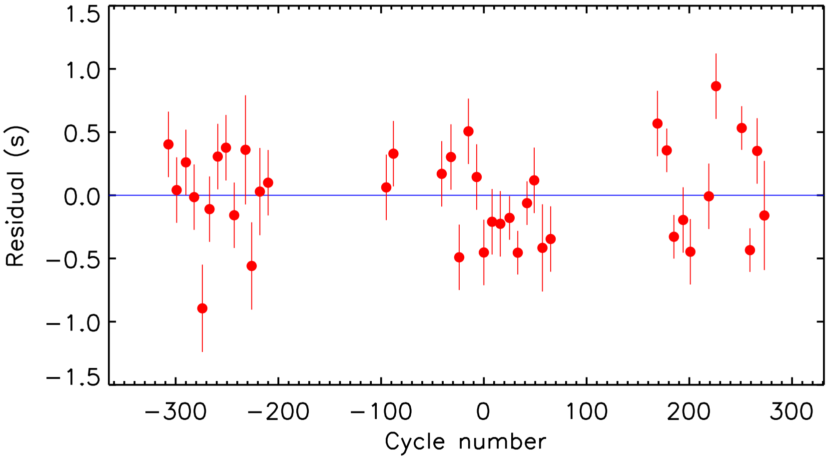

FIG. 4

Residuals of the times of minimum light from Table III (red circles) *versus* the best-fitting ephemerides. The blue solid line indicates a residual of zero. The ordinate axis does indeed show only ±1·5 seconds.

and more precise than either photographic study, we adopt our fit to the M05 RVs (with separate systemic velocities) as the spectroscopic orbit of BS Dra in the following analysis. A plot of the RVs against our fits is in Fig. 5. If we had instead taken the weighted mean of all three $K_{\rm A}$ and $K_{\rm B}$ values we would have obtained 97·9 ± 0·7 and 98·8 ± 0·6km s^{-1}. In the near future new RVs from *Gaia* DR4 will be available for checking the $K_{\rm A}$ and $K_{\rm B}$ values for this system.

Physical properties and distance to BS Dra

We used the $r_{\rm A}$, $r_{\rm B}$, and i values from Table II, the orbital period from the ephemeris given above, and the $K_{\rm A}$ and $K_{\rm B}$ values from Table IV to determine the physical properties of the BS Dra system. The calculations were performed using standard formulae[41] implemented in the JKTABSDIM code[42], which propagates uncertainties from the input to the output parameters by perturbation. The results are given in Table V.

M05 gave the effective temperature ($T_{\rm eff}$) of our star A (which is their secondary star) as 6626 ± 153 K from spectral fitting. Our J from Table II corresponds to a $T_{\rm eff}$ difference of 11 K. Putting these measurements together and rounding to 10 K gives the values we adopted (Table V).

Our mass and radius measurements have precisions of 1·3% and 0·4%, respectively, which is significantly better than previous analyses have given[17,24,25] and the first time all values have been obtained to 2% precision. We note, however, that adopting the weighted-mean velocity amplitudes from the end of the previous section would increase the values of the masses by 2·1% for star A and 2·8% for star B.

To estimate the distance to the system we used the BV magnitudes from *Tycho*[9], the $JHK_{\rm s}$ magnitudes from 2MASS[10] (corrected to the Johnson system using transformations from Carpenter[44]), the stars' physical properties from Table V, and calibrations of surface brightness *versus* $T_{\rm eff}$ from Kervella *et al.*[45] The optical and infrared distance estimates agree with the inclusion of an interstellar reddening of $E(B-V) = 0{\cdot}05 \pm 0{\cdot}02$ mag. The best distance estimate is 191·3 ± 2·9 pc based on the $K_{\rm s}$ band, which is in acceptable agreement

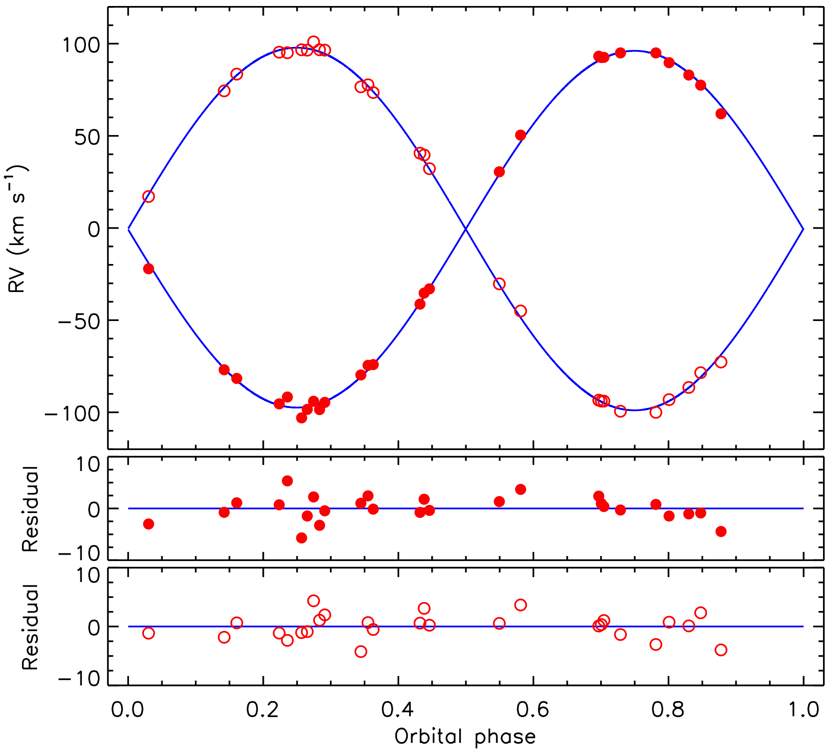

Fig. 5

RVs of BS Dra from M05 compared to the best fit from JKTEBOP (solid blue lines). The RVs for star A are shown with filled circles, and for star B with open circles. The residuals are given in the lower panels separately for the two components.

Table V

Physical properties of BS Dra defined using the nominal solar units given by IAU 2015 Resolution B3 (ref. 43).

Parameter	*Star A*	*Star B*
Mass ratio M_B/M_A	0·9837 ± 0·0077	
Semimajor axis of relative orbit ($\mathcal{R}^N_\odot$)	12·974 ± 0·051	
Mass ($\mathcal{M}^N_\odot$)	1·305 ± 0·015	1·284 ± 0·017
Radius ($\mathcal{R}^N_\odot$)	1·4092 ± 0·0056	1·4001 ± 0·0055
Surface gravity (log[cgs])	4·2559 ± 0·0022	4·2544 ± 0·0027
Density ($\rho_\odot$)	0·4665 ± 0·0020	0·4679 ± 0·0021
Synchronous rotational velocity (km s^{-1})	21·19 ± 0·08	21·06 ± 0·08
Effective temperature (K)	6630 ± 150	6620 ± 150
Luminosity $\log(L/\mathcal{L}^N_\odot)$	0·539 ± 0·039	0·530 ± 0·040
$M_{\rm bol}$ (mag)	3·39 ± 0·10	3·41 ± 0·10
Interstellar reddening $E(B-V)$ (mag)	0·05 ± 0·02	
Distance (pc)	191·3 ± 2·9	

with the parallax distance of 195·34 ± 0·50 pc from *Gaia* DR3[11].

We estimated the age of the system by comparing the measured masses, radii, and $T_{\rm eff}$s to theoretical predictions from the PARSEC 1·2 evolutionary models[46]. The best fit occurs for an age of 1600 ± 150 Myr and a fractional metal abundance by mass of $Z = 0{\cdot}014$. An age of 1700 ± 150 Myr matches the masses and radii for $Z = 0{\cdot}017$, but the predicted $T_{\rm eff}$values are slightly low. No solution can be found that matches the radii and $T_{\rm eff}$s of the components, for their measured masses, for $Z = 0{\cdot}020$ or $Z = 0{\cdot}010$. These results agree with the suggestion by M05 that BS Dra is mildly metal-poor.

Stellar activity

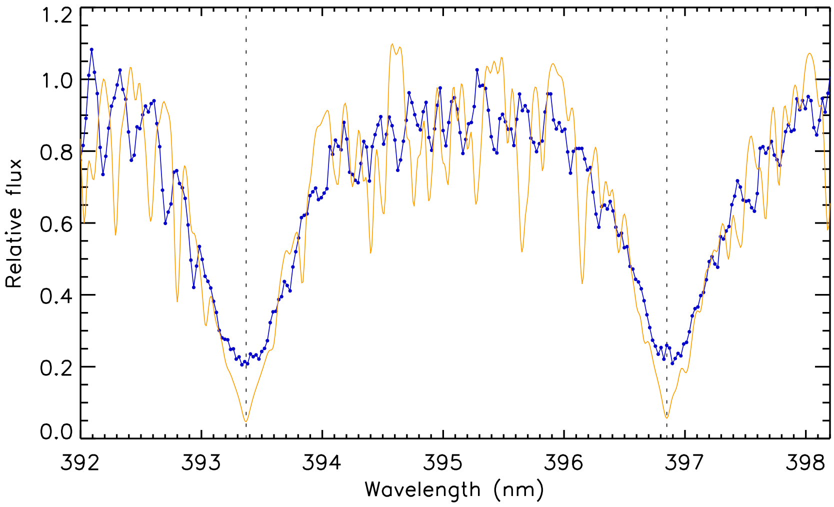

Fig. 6

Observed spectrum of BS Dra around the Ca II *H* and *K* lines (blue line with points) compared to a synthetic spectrum for a star with $T_{\rm eff}$ = 6630 K, log g = 4·0, and solar metallicity from the BT-Settl model atmospheres[47,48] (orange line). The *H* and *K* line central wavelengths are shown with dotted lines. The spectrum of BS Dra has been shifted to zero velocity and normalized to approximately unit flux.

We obtained one spectrum of the Ca II *H* and *K* lines of BS Dra on the night of 2022 June 7 to search for emission lines due to chromospheric activity. We used the *Isaac Newton Telescope* (*INT*) and *Intermediate Dispersion Spectrograph* (*IDS*), with the 235-mm camera, H2400B grating, EEV10 CCD, a 1-arcsec slit, and an exposure time of 300 s. The data were reduced using a pipeline currently being written by the author[49], 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 has a resolution of approximately 0·05 nm, a reciprocal dispersion of 0·023 nm px^{-1}, a coverage of 373–438 nm, and a signal-to-noise ratio of 45.

The observation was obtained at an orbital phase of 0·905, when the RV separation of the stars was 109 km s^{-1} (0·144 nm). Fig. 6 shows the spectrum compared to a synthetic spectrum of the same atmospheric parameters from the BT-Settl model atmospheres[47,48]. The Ca II *H* and *K* lines show some infilling as expected from chromospheric emission, but no variations due to starspots are seen in the *TESS* light-curves. This suggests that BS Dra has chromospheric activity but negligible starspot activity.

Summary and conclusions

We have presented an analysis of the dEB BS Dra, which contains two almost identical F3 stars in a circular orbit of period 3·36 d. We have determined the masses of the stars to 1·3% and their radii to 0·4%, using new light-curves from 40 sectors of the *TESS* mission and published spectroscopic results. For the first time we clearly detect a difference in depth between the primary and secondary eclipses, allowing a definitive assignation of which is the primary star. We showed that it is slightly but significantly hotter, larger, and more massive than its companion. The distance we found to the system agrees with the *Gaia* DR3 parallax.

The eclipses are deep and triangular in shape, a morphology that is optimal for measuring precise eclipse times. We determined one overall time of primary eclipse per *TESS* sector, from all primary and secondary eclipses in that sector. The measurements have a remarkably low scatter of 0·37 s around the best-fitting linear ephemeris, indicating that BS Dra may be useful in checking the timings of future datasets. This has already been done for *TESS* by von Essen *et al.*[50], who found the satellite's timings to be 5·8 ± 2·5 s earlier than ground-based observations of 26 binaries showing deep eclipses. Similar dEBs may be useful in cross-checking timings of the *TESS* and forthcoming *PLATO*[51] missions.

By comparing the physical properties of BS Dra to theoretical models we deduced an age of 1600 ± 300 Myr and a slightly sub-solar metallicity. More precise $T_{\rm eff}$ measurements would be helping in refining the age; a spectroscopic metallicity measurement would also permit the reliability of the models to be assessed.

The stars are hot enough to show δ Scuti or γ Doradus pulsations, and such a discovery would be scientifically valuable[52,53]. We thus checked for any pulsations in the system by calculating the frequency spectrum of the residuals of the JKTEBOP fit to sectors 47–60, using version 1·2·0 of the PERIOD04 code[54]. None were found in the frequency interval 0–100 $\rm d^{-1}$ to a limit of 10^{-5} mag.

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REVIEWS

Women in the History of Quantum Physics: Beyond Knabenphysik, edited by Patrick Charbonneau, Michelle Frank, Margriet van der Heijden & Daniel Monaldi (Cambridge University Press), 2025. Pp. 470, 25 × 18 cm. Price £37·99 (hardbound; ISBN 978 1 009 53583 0).

This well-written and rigorously researched volume documents the career histories of 16 women who carried out critical experimental research for quantum physics during the 20th Century. It does more than describe their achievements (and occasional frustrations) in this budding discipline; science had already been grasping at the reality of quantum physics in counterposition to classical physics, and needed but high-quality experimental proof to verify theories that were being suggested. It was actually Williamina Fleming (an astronomer, no less) who set the ball rolling here by recognizing that the spectrum of singly ionized He in hot stars mimicks the pattern of a hydrogenic sequence, thereby contributing verification for Bohr's model of the atom. Others then built upon her result from numerous standpoints that particularly included laboratory experiments — a professional activity in which women definitely excelled.

These 16 women represent a fairly broad geographical spectrum, though with a greater emphasis on Spain, Portugal, and Latin America than was the case for the 40 female astronomers who emerged successful according to *The Sky is for Everyone*[1]. Despite the positive vignettes portrayed in astronomy by that publication, its review in *The Observatory*[2] concluded that concentrating on the minority who were either fortunate or favoured did a disservice to the discipline as a whole, since the majority of those initially aspiring to careers in astronomy research left the field for whatever reason, and that the 'leaky pipeline'[3] had not been closed. The same biasses have still seemed to prevail in quantum physics, regardless of ethnicity or background.

So what went wrong? Why the need for a book like this one? The sad evidence is that the disadvantages, discriminations, and negativity of gender-based instances influenced progress in this field every bit as much as they have done in astronomy. What is chronicled here should therefore be given a place in every library that features the history of science. Even though it specifically tries to avoid selecting only those who made it to the 'top', we see a common trend. Most of its subjects were high-fliers at school and university, but all too quickly discovered that, whether through the pettiness of local politics, the constraints of motherhood, or the common assumptions that the male partner in a two-body cooperation is the prime author, for them the career ladder had already become the career *cul de sac*, and for no other clear reason than their gender.

In quantum physics as in astronomy, beneficial changes may now be in sight but at a relatively glacial pace, and it will probably take many more books like this present one to paint the accurate picture as to where and why half of the incipient workforce and high-quality brain power silently disappears from sight. In some cases, the achievements of the women whose work proved so fundamental to the progress realized by quantum physics in the 20th Century are preserved in the name of the male partner alone, thus denying them due recognition even as researchers in their own right.

Will we never learn? — Elizabeth Griffin.

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Annual Review of Astronomy and Astrophysics, Volume 63, 2025, edited by E. van Dishoeck & Robert C. Kennicutt (Annual Reviews), 2025. Pp. 523, 24 × 19 cm. Price from $481 (print and on-line for institutions; about £360) (hardbound; ISBN 978 0 8243 0963 3).

Sadly, the latest volume of *Annual Review* does not start with the traditional autobiographical account by one of astronomy's grandees, but is nonetheless full of beautifully presented accounts of the hot topics in the field.

Planetary science looms large this year with the formation of giant planets discussed by Ikoma & Kobayashi, be they local or around more distant stars. With observations from ground-based and space telescopes, we can now examine the spectra of exoplanet atmospheres, as revealed by Snellen, while Vidotto models the interactions those exoplanets may have with their host stars. A further article on exoplanet research is that by Kenworthy & Haffert showing how high-contrast coronagraphy can now be used to probe such systems.

Moving on to stars, their formation processes, for both high- and low-mass objects, are compared and contrasted in the leading paper by Beuther *et al.* Perhaps the most interesting topic for me was the discussion of 'Blue Stragglers & Friends' by Mathieu & Pols, in which the results of binary interaction during evolution is now seen to produce not only blue stragglers — a field in which I once wandered — but also yellow stragglers.

Edging on to more massive objects still, a comprehensive study of how galaxies come together — entitled 'Extragalactic Archaeology' — is described by van de Ven *et al.*, while the kinematics of the Local Group is considered by Strigari. Coming on to high-energy matters, the impact of ionizing radiation from galaxies on the intergalactic medium is outlined by Jaskot; X-rays from AGN due to super-massive black holes are considered by Kara & García; energy production by relativistic magnetic reconnection sparked by black holes and neutron stars is described by Sironi *et al.*; and the nature and origin of ultrahigh-energy cosmic rays are whimsically portrayed by Globus & Blandford. — David Stickland.

The Solar System, by William Sheehan & Clifford J. Cunningham (Reaktion), 2025. Pp. 407, 22 × 18 cm. Price £25·00 (hardbound; ISBN 978 1 83639 064 0).

This work published by Reaktion Books, one of thirteen volumes in a series edited by Peter Morris entitled *Kosmos*, investigates historical, contemporary and future developments in Solar System astronomy. Both authors are accomplished writers and researchers, uncovering many new insights into what could be considered a well-worn subject. They have created both a fine literary work and an accurate and authoritative account that has been a pleasure to read. Their commanding use of the English language is impressive. Be prepared both to be entertained by their prose and to learn some deeper truths about stories from the past. Evidence of their in-depth knowledge is provided by way of 19 pages of references covering the ten chapters of text and splendid illustrations.

In many places, they write to put the historical record straight given that 2025 provides the truest perspective yet of observational astronomy over the centuries leading up to the Space Age, and the almost seven decades of space-probe exploration of the Solar System since — a privileged vantage point indeed! A nice touch used throughout the book, which makes it very readable, is the wealth of apposite quotations and extracts from the literature, not only scientific but also many of literary merit. Some are verbal quotes — well-founded views of astronomers currently working in the relevant field.

I would have liked more detail in the last chapter, 'The Outer Solar System', in that it covers a diverse range of topics, including interstellar objects, yet occupies only one-eighth of the main text. The style is necessarily more concise there than in the rest of the volume. Illustrations and new findings made possible thanks to the *James Webb Space Telescope* are included, as are many fine *HST* and space-probe images, but more could have been made of the future impact of high-tech ground-based observatories such as *Rubin* and the *E-ELT* that are coming on-stream in the present decade.

The writers have also between them authored other books in the *Kosmos* series covering the topics of *Mercury*, *Venus*, *Asteroids*, *Jupiter*, and *Saturn*. Bill Sheehan particularly has been a prolific life-long writer and his passion for Solar System studies is plain to see. It's not so surprising that this most recent publication is one of the very best to have been written with respect to the Solar System. — Richard Miles.

Discordance: The Troubled History of the Hubble Constant, by Jim Baggott (Oxford University Press), 2025. Pp. 328, 24 × 15 cm. Price £20 (hardbound; ISBN 978 019 286406 2).

Recently, I reviewed a book in these pages by Baggott & Heilbron[1]; this book is dedicated to John Heilbron, who died around the time their joint book was completed. In about 1975, I read one of the many books I've read by Isaac Asimov[2]; despite being the title of the book, the neutrino doesn't appear until about half-way through. Asimov spent the first half of the book on the history of conservation laws, which of course are essential for understanding why the neutrino was originally postulated, and why it was accepted long before it was actually discovered. Baggott follows a similar but more exteme approach, with the Hubble tension appearing only in the tenth and final chapter. The Hubble tension refers to the fact that 'local' measurements of the Hubble constant H ($\dot{R}/R$, where R is the scale factor of the Universe; often, H_0 is discussed, where, as with other cosmological parameters, 0 refers to the value today) tend to give a higher value (≈ 73 km/s/Mpc in the usual units) whereas deriving H_0 from measurements of the cosmic microwave background (CMB) tends to give a lower value (≈ 67). Older readers might remember when the tension was between 50 and 100. The situation today is different, though. The Hubble tension of a few decades ago was primarily between different groups (with Allan Sandage and his followers favouring low values, sometimes even lower than 50, and Gérard de Vaucouleurs and collaborators preferring high values), whatever methods they used. Today, it is primarily between different methods, the size of the error bars has decreased proportionally by more than the difference between the two values (resulting in a statistically significant tension), the cause of the tension is not as clear, and it is more common to see it as possible evidence of new physics. There is also tension *within* the high-value camp, with Adam Riess and collaborators preferring a somewhat higher value while Wendy Freedman and her team advocate a lower value with of course less tension with the CMB value but perhaps even without a significant statistical discrepancy.

I'm not sure why the zeroth chapter is a prologue rather than a proper chapter (at 15 pages, it is only slightly shorter than the other chapters, which average about 25); it introduces the basics of stellar astrophysics. From there, we get nine chapters which introduce enough cosmology (often in the form of a historical narrative, and including many quotations) to place the Hubble tension in the proper perspective: Leavitt's law; the scale of the Universe; the Hubble constant; Lemaître's cosmology, stellar populations, Big Bang nucleosynthesis, and the cosmic microwave background; cosmological parameters; the much larger Hubble tension of a few decades ago and the debate between the low value of Sandage and the high value of de Vaucouleurs; inflation; dark energy and the accelerating Universe; and the standard or concordance model of cosmology. Of course, many books have been written about each of those topics; the still rather long summary here is intended to set the background for the Hubble tension, but is a good summary in itself.

Baggott gets some things right which many authors get wrong, such as the explanation of the cosmological redshift. But he makes common mistakes (about which I've complained in many reviews in these pages) by recounting the relationship between geometry and destiny*

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*If there is no cosmological constant, a spatially closed universe will collapse after initial expansion, whereas for a universe with no cosmological constant as if that applied in general (it doesn't, and in particular doesn't appy to our Universe) and by implying that the recession velocity of galaxies cannot exceed the speed of light c. The latter is especially strange in a book on the Hubble constant: $v = HD$ where v is the recession velocity and D is the distance; if D is large enough, v can exceed c[4,5]. He mentions that, trivially of course, a change in the rate of expansion would show up as a deviation from a straight line in a plot of the scale factor as a function or time, but also that that would lead to deviations from a straight line in "the plot of redshift vs magnitude or distance"; in the latter case, one would expect deviations from a straight line for other reasons as well. A few pages later is the huge mistake of claiming that the relativistic Doppler formula is somehow relevant for cosmology "as recession speeds approach the speed of light". While it is true that $v \approx cz$ is no longer valid at high redshift, that doesn't mean that the relativistic Doppler formula is, and it most certainly isn't. An easy way to see that is that the relativistic Doppler formula contains no cosmological parameters, not even the Hubble constant. Are we expected to believe that recession velocity as a function of redshift is independent of the cosmological parameters? (To be sure, the non-relativistic Doppler formula doesn't contain any cosmological parameters either, but it is valid because things are linear to first order.) If I were granted one wish, it might be that everyone interested in cosmology read and understand refs. 4 and 5. I give credit to Baggott for quoting from Dicke's Jayne lecture, but the discussion of the flatness problem ignores the literature on that topic after 1979, even though several well known cosmologists have questioned the standard interpretation (*e.g.*, ref. 6 for a review). Also annoying is the claim that inflation, dark matter, and dark energy were all introduced as *ad hoc* solutions to various problems. While the evidence for them might not be as strong as for other things, the truth is more complex. Other strange statements occur, such as that one can calculate the m–z relation for a flat universe with different values of the density parameter Ω_M (clearly labelled on the example figure from the literature) "with no assumptions about the value of Ω_Λ"; for a flat universe, $\Omega_\Lambda = 1 - \Omega_\mathrm{M}$.

On the other hand, it is refreshing to see a discussion of flat galaxy rotation curves start with the work of Babcock. (But crediting Zwicky as the discoverer of dark matter makes sense only if that is qualified (which Baggott doesn't do): Zwicky was the first to suggest that there could be much more dark than luminous matter, though the importance of that was not appreciated until it was realized that most cosmological dark matter cannot be baryonic.) The discussion on CMB cosmology in Chapter 9 is very good. And Chapter 10, the one actually about the Hubble tension, gives a good overview.

Familiar is the story of Hubble finding a Cepheid in what is now known as the Andromeda galaxy and thus discovering that it is far enough away to be outside the Milky Way and be a galaxy (even larger than the Milky Way) in its own right. Baggott mentions that not only had that Cepheid been discovered by Humason, but that Humason had approached Shapley, suggesting that it could be used to measure the distance to Andromeda. However, before leaving for Harvard, Shapley erased Humason's marks from the plate. That story is also told by Christianson[7], but I had forgotten it, probably because Christianson recounts many episodes in which Hubble took more than his share of the credit. Other material is more familiar, such as Lemaître publishing in French in the "obscure journal" *Annales de la Societé Scientifique de Bruxelles*, a fact that has been mentioned so many times that it

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one which is flat or negatively curved will expand forever. One might thus grant some poetic licence in referring to a universe which will collapse as 'closed' — perhaps closed in time, whatever its spatial curvature. However, describing the Einstein–de Sitter universe, which is spatially flat and thus infinite in extent but with a rate of expansion which asymptotically approaches zero as having "just enough density of matter to halt the expansion and close the universe after an infinite amount of time" is going too far. On another page, it is claimed that in the Einstein–de Sitter universe, not only will expansion stop, but the scale factor will go back to zero after an infinite time; there is no interpretation in which that make sense. Interestingly, there is a long history of referring to such borderline cases as closed.[3]

has made that journal one of the most famous in cosmology! (It was also not as obscure at the time as is sometimes claimed.) While it is true that his paper on relativistic cosmology[8] had little impact at the time, that is also true of Friedmann's papers[9,10], even though they were published in German, as was much of the astronomical literature at the time, and in *Zeitschrift für Physik*, a leading journal. (Baggott does note that Friedmann overlooked the flat $k = 0$ case, first discussed by Robertson[11].[*]) Baggott gives Lemaître credit for first calculating what would later be known as the Hubble constant[†], but misses the important detail that his "of no actual interest" is almost certainly a too literal translation of *actuel*, which means 'current' in French[12].

I found the discussion of the de Sitter universe (a universe with no matter and a cosmological constant; the expansion is exponential and the Hubble constant constant in time[‡]) somewhat confusing, as it is presented as a universe with positive spatial curvature, whereas most modern cosmology books describe it as being flat. Either is correct, depending on the coordinates chosen. However, the explanation is too complicated (*e.g.*, ref. 13) to be explained in such a book; the slightly ahistorical modern description might be more appropriate.[§]

The epilogue briefly discusses a few ideas which have been inspired by the Hubble tension and/or possible explanations for it. It is not intended to be a thorough discussion but rather to put the Hubble tension in context. Three appendices cover symbols and acronyms, cosmological distances, and lookback time as a function of redshift. There are several black-and-white illustrations scattered throughout the text. A page of acknowledgements and more than three of figure and photo credits indicate what a vast undertaking such a book is, even more so because the subject is very current. Somewhat unusual is that photos (of people) and other figures are numbered separately (though of course images of galaxies taken with photographic plates are certainly photos in the normal sense of the word). There are no footnotes but a bit more than seventeen pages of endnotes, most of which are references. The bibliography of about two-and-one-half pages is a list of books for further reading and/or background material used by the author (as opposed to the explicit references in the notes). A thirteen-and-one-half-page index ends the book.

I would like to have liked this book more. The introductory chapters on (the history of) astronomy and cosmology are interesting and useful and, though tailored to the theme of the book, often present more than just the standard material. The material on relatively new observational cosmology (CMB, baryon acoustic oscillations, and the Hubble tension itself) is good. The book is well written at an appropriate level and it is useful to have such books on current topics. However, any recommendation has to be tempered by several at best misleading statements about cosmology, most of which I've seen elsewhere. That is part of the problem: I doubt that most authors make the same mistakes independently. Rather, mistakes in the source material live on in newer works, and it would be a shame if an otherwise good book by a well-known popularizer of science keeps that trend alive. It provides a good overview of the Hubble tension, why it is important, and the necessary

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[*] Although that model was later discussed by Robertson and others, his doctoral thesis is certainly more obscure than Lemaître's paper in French.

[†] While the IAU voted to rename the Hubble law the Hubble–Lemaître law, the constant is still just the Hubble constant.

[‡] In general, the Hubble constant is not constant in time. However, that is not a misnomer; it is the constant in the equation $v = HD$. Thus I disagree with Baggott who claims that it should be called the 'Hubble parameter' for that reason. By contrast, the cosmological constant *is* constant in time. The de Sitter model has other features which are not true in general, *e.g.*, the Hubble radius is also the radius of the event horizon.

[§] Readers of German might want to consult a doctoral thesis[14] by the same author as that of ref. 13 for more background on de Sitter's role in the early days of relativity and relativistic cosmology. Although Eddington is well known as a champion and popularizer of General Relativity, de Sitter was as well, *e.g.*, very soon after the initial paper by Einstein[15], he wrote a 'popular' summary in these pages[16] as well as more detailed explications[17–19].

background to understand it, but readers should get their overview of cosmology from elsewhere. — Phillip Helbig.

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From Stars to Life: A Quantitative Approach to Astrobiology, by Manasvi Lingam & Amedeo Balbi (Cambridge University Press), 2024. Pp. 400, 26 × 21 cm. Price £59·99/$79·99 (hardbound; ISBN 978 1 009 41121 9).

Astrobiology is perhaps the most multidisciplinary science that can be imagined. Everything, from cosmology to biology, planetary science to astrophysics, is involved at some level, and a detailed understanding of the history of life on Earth is also necessary since we have but one place where the emergence and evolution of life can be studied. In fact, if we go so far as to include the search for extraterrestrial intelligence, we must add human history and sociology to the mix. This extreme multidisciplinarity means that many textbooks that cover astrobiology take separate chapters written by multiple authors and edit them together to produce the final work. That is not the approach taken here as the authors bravely take on the vast epic that is the story of life in the Universe from the Big Bang to the present day and beyond. And in doing that they are largely successful, maintaining a coherent voice and approach throughout. The book starts with the large-scale boundary conditions provided by cosmology and then moves to the astrophysics of stars and planet formation. The Earth is then studied in detail, including its early conditions, then looking at the possible routes through which life might have originated here, and how life both affects and is affected by the terrestrial environment. The lens then zooms out to look at broader questions of habitability elsewhere, before potential astrobiological targets, inside and outside the Solar System, are discussed. The astrophysical techniques for detecting life elsewhere, including intelligent life, are then examined. The book's subtitle is 'a quantitative approach' and there is indeed a decent amount of quantitative analysis both in the text and in the included problems. However, the squishy and at times speculative nature of the field makes it inevitable that a fair fraction of the problems are more wordy than quantitative, and try to send the reader off to the broader literature to come up with their own hypotheses and analyses. Such explorations would certainly be rewarding, but, in a world where students increasingly use Large Language Models to answer such homework questions, they may be less useful in a formal teaching environment. The goal of the book, to cover the field of astrobiology in its true breadth, from stars (and even from before stars form) to life, is fully achieved, and there will almost certainly be something new here for anybody involved in astrobiology. Highly recommended, and already added to the reading lists of relevant courses that I teach. — Dave Clements.

The Blue Straggler Mystery, by Martin Beech (World Scientific), 2026. Pp. 271, 23·5 × 15·5 cm. Price £55 (hardbound; ISBN 978 981 98 2008 5).

Blue stragglers are stars that lie in the vicinity of the main sequence in a cluster colour–magnitude (or HR) diagram, but bluewards of the cluster turn-off. The 'mystery' is, or rather, was, how they come to be there when, in the simplest scenarios, they should've evolved away to the red. This nicely produced little hardback (also available as an e-book) pursues that question, using the device of allusion to detective fiction (particularly Sherlock Holmes) to frame the chase.

This is more a scholarly book than a 'popular' one, though written in a relaxed narrative style. The first two chapters — roughly half the page count — present a primer in basic stellar astrophysics ('The measure of the stars', 'How the stars work'), with the third ('Making blue stragglers') reviewing the historical development of solutions to the 'mystery'. A final 50-page chapter ('And finally. . . ') is a speculative ramble touching on topics as diverse as alien civilizations, black holes, artificially engineered stars, and much else that seemed to me to be only tenuously linked, at best, to blue stragglers. Simple equations are sprinkled throughout the text (minimal calculus and no derivations), as are graphs and other diagrams, along with a few astronomical images. Colour is used to good effect, and each chapter is supported by a page or two of references. There is no index.

The acknowledgements don't include a nod to anyone for proof-reading the manuscript, which may explain the smattering of infelicities and oddities. Pretty much all are harmless (*e.g.*, are radio astronomers really not observers [p. 34]? Was a wide-field, shallow image of the Pleiades really obtained with *HST* [p. 57]?) or even amusing (stars "sliming down" [p. 88]), although the naïve reader may wrongly infer that neutron-star magnetic fields are a proximate consequence of convection [p. 137]. A forceful editor may've also reined in the author's rather intrusive predilection for the word 'indeed'.

Regardless of these trivial quibbles I found the book to be an engaging and pleasant enough read, even if the content of the last chapter wasn't much to my taste. The real mystery for me was: for whom is the book intended? It's too technical for a general readership; didactic, but not suitable for use as a textbook; and the principal topic is so narrow that the interested researcher is likely to go directly to the primary literature. I therefore turned to the World Scientific website, where I learned that, apparently, the "target audience for this book is the undergraduate science student, and the informed, general-reader on topics relating to astronomy and physics." Elementary. — Ian D. Howarth.

Crush: Close Encounters with Gravity, by James Riordon (The MIT Press), 2025. Pp. 287, 23 × 15 cm. Price $29·95 (about £22) (hardbound; ISBN 978 0 262 05098 2).

This might be the only book to discuss both event horizons and the anatomy of snakes.

The name James Riordon seemed familiar to me, but probably because I was thinking of James Riordan, who played a role in the *Apollo 13* mission. Or perhaps because I had come across something else by the author, NASA-affiliated science writer James Riordon. Confusingly, the author's father (also James Riordon) also worked for NASA, on the Apollo and Space Shuttle programmes. (Finally, an internet search for 'Riordon' and 'Apollo' will probably find Rick Riordon, author of *The Trials of Apollo*, who has written many books for children which adapt ancient Greek and other mythologies for a modern readership.) This is a book about gravity, but, compared to the books about General Relativity (GR) I've reviewed in these pages, it takes a very broad view of its topic.

It starts off familiar enough, with a short zeroth chapter on Newton. The next two chapters discuss the effects of gravity on humans and other animals. (The position of the heart in a snake depends on whether it lives mostly underwater, crawls on land, or climbs trees; the different positions are adaptations to the different effects of gravity on blood circulation.) While its effects on humans are of course familiar to me, there is much fascinating information on various experiments involving animals and their relation to gravity (mice suspended by their tails, leaping nematodes, *etc.*). The fourth chapter (Chapter 3) brings us back to astronomy, discussing the effect of gravity on the properties of planets. The next three chapters are a more-or-less standard overview of the history of gravity in physics, but with many details on Maupertuis, Cassini, and measuring the shape of the Earth. Special Relativity and GR are introduced, and there is a good discussion on measurements of the gravitational constant G, which is still the physical constant with the least-precise value.

We are then introduced to the flowing-space interpretation of GR.[*] That is a simple example of the otherwise rather technical idea of 'analog gravity', and for many might provide a more intuitive understanding of GR. There is also an appendix describing concrete experiments one can do in a kitchen sink, with flowing water standing in for flowing space.

We are back in more-standard territory with the discussion of gravitational waves, which starts with a quote from Joseph Weber: "They'll put a bullet in my head." That is from one of the first interviews in the author's science-journalism career; it was also the last interview ever with Weber, who was willing to talk but only after being promised strict confidence as long as he was alive. (Weber died not long after the interview, but from lymphoma[†], rather than a bullet from the National Science Foundation or anywhere else.) When an undergraduate at the University of Maryland, Riordon knew Weber, who features prominently in the acknowledgements, as one of his professors. Riordon notes, though, that "Joe Weber may not have detected gravitational waves" and that his Lunar Surface Gravimeter, placed on the Moon by the *Apollo 17* astronauts, never worked either.

Chapter 9 gives an overview of various ideas for quantum gravity, and the next one of dark matter and dark energy. Those are familiar topics for myself and presumably many readers of this *Magazine*. Like the rest of the book, it is well written and essentially correct (see below for a few common mistakes in other areas). However, despite mentioning Milgrom and Finzi and their ideas of modified gravity — rarely mentioned in popular-science books — , the dark-matter story is essentially limited to Rubin (and — also rare — her long-time collaborator Ford) and Zwicky; Babcock, Bosma, and Roberts should at least be mentioned. There is the familiar trope of Rubin not getting enough credit for her work and even being overlooked for a Nobel Prize (though the common claim that that was due to sexism is not repeated).[‡] Interesting, though, is a quotation from Rubin: "Only the future will tell us

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[*] In contrast to various interpretations of Quantum Mechanics, different ways of looking at GR, such as the standard way involving curvature, the flowing-space interpretation, the membrane paradigm, *etc.*, do not differ in their claims about the underlying physical reality, but rather are just different approaches, with a certain approach more mathematically convenient for certain problems.

[†] I survived lymphoma twice; the first time in 2004. At least for my type of lymphoma, much progressed had been made in the few years immediately before, in particular the introduction of rituximab.

[‡] No Nobel Prize has been awarded for the discovery of dark matter; had one been awarded while she was still alive, my guess is that she would have been one of three recipients, though which of the three still alive then would have been a difficult decision — but the difficulty of such a decision is almost certainly not the reason for not awarding a Prize at all. Ford died in 2023, Roberts in 2024; of the obervational pioneers, only Bosma is still alive. To some extent, the award to Peebles recognized his theoretical work on the role of dark matter in astrophysics and cosmology.

what dark matter is, or whether our lack of knowledge of gravitation on the largest scales has fooled us." In other words, Rubin herself wasn't sure whether she had discovered dark matter. (She also cited her predecessors in the field of flat rotation curves.) Other methods of finding evidence for dark matter are covered, such as 'direct' detection in the lab (*via* a rare interaction between a dark-matter particle and an atomic nucleus), observing radiation from the decay or annihilation of dark-matter (anti)particles, and creating such particles in an accelerator. (Those methods are often dubbed 'shake it', 'break it', and 'make it'; if modified gravity rather than dark matter is responsible, then that would be 'fake it'.) The discussion of dark energy is brief, but that topic is only mildly relevant to the main subject of the book.

The next chapter covers more speculative aspects of GR: white holes, worm holes, naked singularities, time machines, and warp drives, and points out the impossibility of anti-gravity devices. Other cutting-edge topics such as 'dark stars' (not dark, but rather powered by the annihilation or decay of dark matter as opposed to fusion), the Multiverse, and theories of everything ("the Moby Dick of gravity") are briefly mentioned.

The last chapter on astrophysics concerns the origin of the elements. While of course many elements are made in stars and gravity plays an important role in stellar structure, gravity plays a more direct role than was assumed until recently as several heavy elements appear to be formed in the collision of neutron stars. One of those is iodine, which is essential for life as we know it. Keeping with the theme of the broad spectrum of the book, the next chapter explores the role of gravity, or the lack of it, in dreams, and the final chapter ties the falling sensation common in dreams to Einstein's 'happiest thought', namely realizing that a person in free fall feels no gravity. The previously mentioned appendix proves that this book contains everything, *including* the kitchen sink. Another appendix contains the only real maths in the book, using the flowing-space interpretation to derive common formulae in GR. I'm surprised that that interpretation is not better known, especially since to most it is probably easier to understand than the concept of spacetime curvature. (It is far from new, having been proposed independently by Painlevé in 1922 (a mathematician who was also prime minister of France) and Gullstrand (a Swedish* ophthamologist) in 1925.)

The breadth of topics covered is also demonstrated by the facts that for the second time in recent book reviews of popular-science books (which normally don't cite the technical literature at all), papers on the long-term future of the Sun[1,2]† are cited — the other book[3] was reviewed[4] in the 2026 February issue of this *Magazine* — as well as three works on life on other planets written by Dirk Schulze-Makuch[5–7] (see the review[8] of another of his works[9] in these pages). Unusual for a book on gravity, there are also references to papers in *Developmental Psychology*, *Clinical Psychology Review*, *Western Journal of Emergency Medicine*, and *Brain Research Reviews*.

Of course, most books I review have a few mistakes, and an honest review must mention them. Kepler's Laws, numbered, are stated, but the second is not the usual one, but rather the (correct) claim that "the Sun isn't at the center of the Solar System, but instead moves on its own, small elliptical orbit". An image of a distant blue galaxy gravitationally lensed into an almost perfect Einstein ring would of course be more impressive if in colour, but the caption mentions those colours with respect to the black-and-white image. The text at least implies that Hulse and Taylor were both at Princeton when they discovered the binary pulsar; they weren't. (Similarly, Adam Riess is now at Johns Hopkins, but wasn't when he did the work leading to his share in the 2011 Nobel Prize.) In contrast to claims in the text, Einstein

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[*] The book makes him Swiss, reminding me of my friend from Vienna who used to wear a sweater with 'There are no kangaroos in Austria' on the front. Ironically, Gullstrand thought that relativity is wrong and used his influence on the Nobel committee to prevent Einstein from receiving the prize for relativity. Even more ironically, Gullstrand was known for his highly mathematical writing, much of which concerned the bending of light — but within the eye.

[†] I heard lectures from the first author when he was an assistant professor and I was a student in Hamburg; the second is a frequent contributor to and former Editor of this *Magazine*.

wasn't directly inspired by the negative result of the Michelson–Morley experiment, perhaps not even indirectly. Nor is inflation characterized by the Universe expanding faster than the speed of light, nor has the Universe "been expanding at a steadily accelerating rate" ever since. (At least he does clearly (and correctly) state that the Universe will expand forever even though we don't know whether it is exactly flat or even the sign of the curvature.) "The fact that something is running down toward an end implies that it also must have had a beginning." No. See ref. 10 for a detailed historical study (which mentions the fact that many *believed* such a claim) and ref. 11 for more recent thoughts on an eternally old cosmos with ever-increasing entropy. There might be a lot of dark matter in the Universe, but its average density is several orders of magnitude less than that corresponding to a small virus in a typical living room as claimed in the book. Although stated just briefly, the text implies that an infinite universe with stars distributed throughout would be infinitely bright and thus that the darkness of the night sky suggests that the Universe has limits. The latter is true, but the limits are temporal; the Universe is not infinitely old. As is the case with most issues in cosmology about which people are confused, Edward Harrison clears them up nicely.[12,13]* (I'm willing to put the comparison of the masses of *two* atoms of hydrogen to one of helium in the context of stellar fusion down to an oversight.) "A tiny bump on a neutron star, roughly as tall as a grain of sand, would result in a detectable signal in LIGO, provided the star is spinning faster than 200 times per second anywhere within a few thousand trillion kilometers of us." Misleading at best: the spin rate is not unrealistic, and the distance is only somewhat closer than the nearest known pulsar. A mountain of height 1 mm, say, might be just possible, given what we know about the crust of neutron stars. But to be detectable by *LIGO*, its area would have to be much, much larger than that of a grain of sand, which doesn't seem very realistic, again based on what we know about the crust of neutron stars.

On the other hand, it was a pleasure to learn some new things, such as Benjamin Franklin showing how a spoonful of oil tossed into the water of Mount Pond in Clapham Common could smooth wind-induced ripples of hundreds over square metres[14]; Franklin was so fascinated by that property of oil (which was known to Pliny the Elder) that he carried a supply of oil in a chamber of his bamboo cane, so that he could demonstrate the effect whenever desired. That was mentioned because the site is near where Cavendish conducted his experiments to measure G and thus the mass of the Earth. Cavendish used an improved version of a pendulum developed by John Michell, usually (and in this book as well) mentioned as probably the first person to come up with the idea of a black hole in the sense of an object with an escape velocity exceeding the speed of light. (While the 'Schwarzschild radius' turns out to be the same, one can move outward across the 'event horizon' of such a 'Newtonian black hole', just not escape to infinity ballistically even if moving at the speed of light when leaving the surface; the event horizon in GR is much stricter.)

There are a few black-and-white figures scattered throughout the text, some due to his daughters (who are also mentioned in the text, one also the subject of a photograph with her head angled down by six degrees to simulate some of the effects of space flight on humans). There are no footnotes; their function is covered by the endnotes, most of which, however, are references (including titles of articles). A couple of pages of 'Further Reading' contain short descriptions of eight books. Sadly, I've read only one completely, parts of another three, and an earlier version of a fifth; the other three are on my (very long) list of books to read before I die. (One of the ones which I've read partly is Newton's *Principia*: "A challenging read due to dated language [not to mention the original Latin], long-winded explanations, and roundabout derivations. Still, it's worth looking over the law of universal gravitation in the words of the genius who revolutionized physics.") A seven-page index ends the book.

Despite my complaints above, I enjoyed reading the book. It is well written and offers a

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*I'm aware of almost a dozen articles as well in which Harrison makes his point, published in a variety of places, including very well-known journals.

fresh take on a subject about which very much has already been written. The few personal anecdotes add to the book rather than detract from it. From biology to Gullstrand–Painlevé coordinates to the psychology of dreams, there is something for everyone here. — Phillip Helbig.

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Machine Learning in Astronomy: Possibilities and Pitfalls (IAU Symposium 368, edited by J. McIver, A. Mahabal & C. Fluke (Cambridge University Press), 2025. Pp. 147, 25 × 18 cm. Price £98 (hardbound; ISBN 978 1 009 34519 4).

Similar to a book[1] reviewed[2] a while back in these pages, this volume of proceedings of an IAU symposium is a mostly bad record of what was probably an interesting meeting. Machine learning (ML), a more prosaic name for artificial intelligence, is all the rage now. However, the symposium took place almost four years ago, and as Ofer Lahav points out in his very good contribution, it was used already in the early 1990s for galaxy classification (at least by Lahav himself and his collaborators). His contribution is perhaps the most interesting for those who don't work in the field, giving a good overview, helped by the fact that he has a background in traditional astronomy but is up to date on the latest ML techniques. Other contributions are more specialized, which is to be expected from the proceedings of a specialized meeting. I have no qualms with that and am not really a member of the target readership. However, starting with the too thin paper (the two covers are almost as thick as all the pages) through which the print on the other side is visible, other production mistakes such as bad editing, lack of consistent formatting, mentioning colours in a book in which all figures are in black and white, and too detailed references lead to a book which is distracting to read, which is unfortunate because the material is new and interesting and relevant not just to astronomy; I found many of the contributions interesting, even though they are far from my own work.

The twenty-seven contributions range from two to seventeen pages and cover topics such as exoplanets, spectra, stars, star clusters, galaxies, gravitational waves, galaxy clusters, and cosmology. The longer contributions can provide a good overview, especially those intended as such, such as Lahav's piece on ML in cosmology or 'An Astronomer's Guide to Machine Learning' by Webb & Good; the two panel discussions also offer something more typical of a conference than the normal literature. Most of the shorter contributions (presumably originally posters) are too short to be of much use: too brief for those not familiar with the topic, and unnecessary for those who are. (While many of the items end with a mostly blank page, the fact that many of the short contributions do so leads to much wasted space.) Interesting to me was that the first contribution, on using ML in exoplanet surveys, starts off by mentioning the exquisite precision of modern spectroscopy, "approaching that needed to detect the motion of a Sun-like start due to the gravity of an Earth-mass planet in its habitable zone", a topic recently discussed in these pages[3]. There are also articles about ML itself; the contribution by Hložek highlights aspects important for astronomy, and the abstract is a good summary of the aims of the entire book. A common theme is not just using ML but understanding how it works, at least at some level of abstraction, though of course the whole point is that ML very probably works differently from human thinking; in that respect it differs from conventional uses of computers, which essentially carry out human-thinking algorithms much faster and/or with much more data.

Apart from the contents, there is a preface, basic information about the editors and the conference, a list of participants, and an author index. Presumably most of the black-and-white figures are originally in colour; that and the fact that some are too small limits their usefulness. The book is produced *via* LaTeX and my hope is that the participants are using BibTeX rather than wasting time; I was thus surprised to see a mismatch between an author name in the text and in the reference list.

In such a fast-moving field, many details will be out of date four years after the meeting, but nevertheless proceedings can provide interesting historical snapshots. However, for a book to fulfill that role, it needs to be produced as a book, or at least in a format (such as that of this *Magazine*) which works both on screen and on paper. All of the contributions are available online, with colour figures, active HTML links, and so on, and that is clearly the preferred format for these proceedings.* Especially considering the price, most buyers of the book will probably be libraries with subscriptions — a common observation in many recent book reviews of such proceedings.

I enjoy going to conferences and well-produced proceedings are both a good record for those who attended an also useful for those who didn't. I think that there are reasons to continue to produce conference proceedings, even if there are fewer such reasons than in the past (*e.g.*, they are no longer practically the only way to get results in advance of publication in the refereed literature — not just the proceedings, but the conferences themselves). Smaller conferences might have to make do with on-line-only proceedings (ideally instead of or in addition to just putting the presentations on the web), which are fine as long as they are permanent. Bigger conferences can justify publishing a book (as well), but if so, it needs to be able to stand on its own. Despite my qualms, I enjoyed reading the book and learned a lot, but am annoyed by the fact that with not much more effort it could have been much better. — Phillip Helbig.

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Dynamical Masses of Local Group Galaxies (IAUS 379), edited by Piercarlo Bonifacio *et al.* (Cambridge University Press), 2025. Pp. 398, 25 × 17 cm. Price $155 (about £116) (hardbound; ISBN 978 1 009 39911 1).

This is the proceedings of the IAU Symposium held in Potsdam in 2023 August. It contains 60 papers, each of reasonable length (no one-page précis), divided into five sections. There are no specific review papers, though a few do cover some history of their topic, and there is no conference overview or afterword, which might have been interesting. The topics are at the same time niche (ostensibly covering just one physical property for a small number of galaxies), yet wide ranging, across *Gaia* surveys, ΛCDM (and other) halos, theoretical stellar dynamics, mergers, and chemical signatures, among others. The final section actually

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*However, only three are open access. Checking which three after I had written this review, I found that — surely not coincidentally — they are the three the authors of which I mention by name.

goes beyond the title of the meeting/book to include near-field cosmology and masses of galaxies outside the Local Group. A drawback of using the book itself is the fact that all the orange circles, blue lines, pink contours, *etc*. are rendered in monochrome, except for one paper with full-colour figures. Also, the review copy I received was poorly constructed, with the first few and last few pages detaching from the binding of the rest. However, as the papers from the meeting are already available online, that hardly matters. Given the price, though the papers themselves are interesting, it is hard to see anyone purchasing this volume beyond libraries with subscriptions to the series. — Steve Phillipps.

Solar Eclipses, by William Sheehan (Reaktion), 2026. Pp. 253, 23 × 18 cm. Price £25 (hardbound; ISBN 978 1 83639 169 2).

With two geographically-close total eclipses of the Sun anticipated during the next 18 months or so, a substantial number of eclipse watchers are expected to travel to Iceland, north-eastern Portugal, Spain, and the Balearic Islands for the event on 2026 August 12, as well as to Gibraltar, southernmost Spain, northernmost Morocco, northern Algeria, central Tunisia, north-eastern Libya, Egypt, and south-western Saudi Arabia for the subsequent eclipse on 2027 August 2. In this context, the release of a new volume on solar eclipses is particularly timely. *Solar Eclipses*, published by Reaktion Books and authored by William Sheehan — a well-known astronomical historian and author of four previous works in Reaktion's *Kosmos* series — distinguishes itself by focussing on the historical dimension of eclipses, rather than merely offering summaries and maps of forthcoming events, as is common in recent publications.

The opening chapter explores the author's personal experiences observing eclipses, providing foundational information on the various types of solar eclipses. Chapter two places eclipses within the context of ancient history, examining how such phenomena may have appeared to nomadic peoples, with discussions spanning Stonehenge, ancient China, South Korea, Egypt, and the Babylonians, before shifting to the Greeks in chapter three. The fourth chapter addresses the complexities involved in calculating the positions of celestial bodies and the prediction of eclipses throughout history. Chapter five delves into the challenges of modelling the motion of the Sun and Moon during the 16th and 17th Centuries, highlighting figures such as Jeremiah Horrocks — who famously described the Sun as "The Impudent Star" —and Edmund Halley's prediction for the 1715 total eclipse. The sixth chapter transitions into the 19th Century, documenting the evolution toward a more scientific approach to eclipse observation, including phenomena such as Baily's Beads and solar prominences, as well as the solar chromosphere. Chapter seven investigates Le Verrier's proposal of the planet Vulcan as a solution to anomalies in Mercury's orbit, and its eventual dismissal with the advent of General Relativity. The concluding chapter outlines the 'coming of age' of eclipse science, detailing the adoption of modern observational techniques on expeditions such as Eddington's experiment during the 'Einstein Eclipse' of 1919 May 29, which prompted the iconic New York Times headline, "Lights all askew in the Heavens". This volume also sheds light on the pivotal role eclipses have played in advancing related fields such as chemistry and physics. Notably, the book includes several rarely seen photographs (at least to me) of influential figures in eclipse science.

Additionally, two appendices address safe eclipse-observation techniques and provide a synopsis of eclipses occurring between 2026 and 2029, both of which are highly commendable and practical. The book is further enhanced by an informative reading list and a comprehensive bibliography. In summary, this is a valuable and well-illustrated addition to any eclipse enthusiast's library, particularly for those interested in the historical and scientific context of eclipses. However, it may not fully meet the requirements of individuals seeking detailed guidance for planning eclipse expeditions in the distant future. Priced at £25, this hardbound edition represents excellent value. As an avid eclipse observer and someone actively involved in almanac calculations and production, I found this work highly rewarding. — Steve Bell.

The Secret Life of the Universe: Searching for the Origins and Frontiers of Life, by Nathalie A. Cabrol (Simon & Schuster), 2025 (originally published 2024; originally published in French 2023 as *À l'aube de nouveaux horizons*). Pp. 315, 20 × 13 cm. Price €16·99 (about £14·89) (paperback; ISBN 978 1 3985 3132 1).

The hardback edition has the subtitle 'An Astrobiologist's Search for the Origins and Frontiers of Life'. In any case, it was translated by the author from her own best-selling book in French. I haven't read the French book, but the English version is extremely good, and based on the text alone I would not have suspected it of being a translation. (Lack of knowledge of the topic is what usually indicates a translation, though occasionally insufficient knowledge of one or both of the languages does so; neither is the case here.) Born, educated, and initially working in France (Observatoire de Paris-Meudon and the Sorbonne), Cabrol and her husband, Swiss-born hydraulic engineer (and after retirement and further studies planetary scientist) Edmond A. Grin (1920–2022), moved to the US, worked for NASA, and became US citizens. She later moved to the SETI institute, becoming the director of the Carl Sagan Center in 2015. Cabrol has 426 entries (135 refereed) at ADS and has been the PI of several NASA projects involving Solar System exploration (including life in extreme environments on Earth).

The book is not just written in good English; some of it is almost poetic: "Rocks made of solid water ice rolled and rounded by time in torrents of liquid methane." ". . . a world where everything looks familiar, yet nothing is really what it seems, and where we could be given a chance to explore side-by-side life as we know it and life as we don't." Having said that, the book is a down-to-Earth (and/or some other Solar System body) account of the one known and many possible abodes of life, starting (after a brief autobiographical sketch) with Earth and moving to Venus, Mars, the Jovian satellites, Titan and Enceladus, the outer Solar System, extra-solar planets (after a chapter on six methods of detecting them). After that tour in nine chapters, discussion turns to the Drake equation, the Fermi paradox, and whether the solution to the latter is some sort of great filter*; and the Kardashev scale, SETI, METI, and UFOs/UAP. Cabrol is clearly someone who would like there to be extraterrestrial life, thinks that it is probable, but, whether regarding microbes on other worlds or visiting aliens, remains true to Sagan's dictum that extraordinary claims require extraordinary evidence. The final chapter is concerned with various attempts at a definition of life (perhaps it is easier to explain the origin of life or to describe what it does than to define it) and related ethical questions. While the earlier chapters give an up-to-date account of topics I was already somewhat familiar with, much of the last chapter, while not always covering completely new ground, introduced me to things such as xenobots. The epilogue is similar to two others[3,4] I've reviewed[5,6] in this *Magazine*, but without the complaint that it seems tacked on; rather, it seems like a logical conclusion, the difference being that it is more related to the main text.

Most of the book is concerned with the Solar System, which is at the opposite end of the scale from my main astronomical interest, cosmology. Nevertheless, I really enjoyed reading the book, and it's good to be brought up to date on topics such as planetary missions by someone actually involved in them. We now know that many Solar System bodies contain water, though not necessarily liquid and on the surface, and Ganymede has more than Earth. Cabrol has a knack for including interesting details without losing sight of the overall picture. I was reminded of many popular-science books which I read as a child and how they inspired and reinforced my interest in science; this book is a fine addition to that illustrious collection.

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*See a somewhat complementary book[1] reviewed[2] in these pages for more on the concept of 'filters' as bottlenecks of evolution.

There are a couple of mistakes which are probably just careless errors and probably most readers won't notice them. I almost always quibble about style, though here less so than is usually the case, and there are few actual typos. There are sixteen pages of colour 'plates' near the middle of the book as well as several black-and-white figures scattered throughout. The former are fine, but the latter could use more detail. Even several years ago I encountered books with high-resolution colour figures printed on regular (as opposed to slick) paper, so I wonder if printing prices really still play a role. Three pages of acknowledgements mention, among others, Frank Drake and Carl Sagan, both of whom she knew personally, as well as her husband. As is to be expected, the four pages of image credits often mention NASA. Somewhat unusually for a popular-science book, there are eight pages of 'Notes' (all references rather than endnotes; neither are there any footnotes); the index of somewhat more than twenty pages is especially thorough. The book is not as long as it looks since it is essentially double-spaced, with enough room for a line of text between two others (by contrast, interline spacing in this *Magazine* is less than 19% of the height of a line; the font size is about the same).

The fact that the French book is a best-seller confirms my impression that there should be a wide readership for such a book, from somewhat older children to the proverbial 'interested layman' to professional astronomers (at least those who don't work in planetary science, but maybe some of them as well). Even those who have read many books on the topic will probably learn something new from this well-written up-to-date book. — PHILLIP HELBIG.

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Here and There

HOW ABOUT PLANET EARTH, FOR EXAMPLE?

Planets smaller than Neptune with a gaseous atmosphere don't exist in the solar system, but they're plentiful around other stars. —*Sky & Telescope*, February 2026, p. 11.

A LUCKY REGION?

MARS can still be seen in the evening sky, although the length of time during which it is visible is rapidly decreasing. After the middle of the month it will be difficult to still see the red planet without binoculars or a telescope. In northern Germany one will search for it in vain. [Original: **MARS** kann noch am Abendhimmel gesehen werden, wenngleich seine Sichtbarkeitszeiten rapide abnehmen. Nach der Monatsmitte wird es schwierig, den roten Planeten noch ohne Fernglas oder Teleskop zu erkennen. In Norddeutschland wird man ihn vergeblich suchen.] —*Kosmos Himmelsjahr 2025*, p. 156

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(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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