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MEETING OF THE ROYAL ASTRONOMICAL SOCIETY

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EMMA BUNCE, *President*
in the Chair

The President. First of all, we're going to hear from Dr. Richard Morton from the University of Northumbria. He was the recipient of the Fowler Award 'G' for 2022. Dr. Morton is currently an associate professor at Northumbria University, working in the Solar Physics and Space Research Group. He is a UK ROI Future Leaders fellow, and his research focusses on investigating magnetohydrodynamic wave propagation in the Sun's atmosphere. Richard is also active in STEM public engagement, and is the public-engagement lead on a European-wide Horizon 2020 research-infrastructure project called SOLARNET. Welcome Dr. Richard Morton to the meeting — I'm looking forward to your presentation, which is entitled 'Revealing the hidden corona with infrared'.

Dr. Richard Morton. It's great to be here with you today, and I'd like to thank the RAS for inviting me to give a presentation. What I'd like to talk about to you today is my work on wave propagation in the Sun's atmosphere, and predominantly how we've looked at waves in the corona in the infrared. The corona had been known for many centuries; however, in the 1850s, when a new instrument called the spectroscope was invented it was pointed at the corona by two scientists called Young and Harkness, and they discovered two emission lines, one in the green at about 530 nanometres and one in the red at about 790 nanometres. They didn't know where they came from, and there were no known elements that would produce them. It took around 70 years for this mystery to be solved. And in the time between, it was proposed that there might even be a new element in the Sun's corona called coronium, which could explain those emission lines.

In the 1930s two astronomers, a German called Grotrian, and a Swede called Edlén, were fascinated in the spectral-line emission from the corona, and they were interested in looking at highly ionized iron atoms and the spectral lines from those atoms. They managed to identify those green and red lines in the corona with forbidden-line transitions within the iron atom. In a side note in the paper, Edlén said that for these lines to appear the corona had to have a temperature of about a million degrees, but he didn't focus on it too much. The idea of a hot corona was really taken forward by Hannes Alfvén in a paper about two years later. However, we still don't understand yet exactly how the corona reaches these temperatures; the mechanisms that are responsible for the coronal heating are still a bit of a mystery. With the realization of a hot corona, it was quickly realized that there should also be emission from the corona in EUV and X-rays, but we can't observe those wavelengths from the ground due to atmospheric absorption, so this meant using space-based observatories.

The first solar observatory in space was actually on board a NASA space station called *Skylab*, which took EUV and X-ray images. *Skylab* made many interesting discoveries whilst it was up there; it was able to identify coronal holes, saw magnetic loops for the first time in the Sun's corona, and discovered short-lived bright emission patches called coronal bright points.

Closely related to the coronal-heating mystery is the solar wind. Back in the 1950s, a British mathematician called Chapman realized that if the corona had a temperature of a million degrees, then it must be an extremely efficient conductor and there must be a flow of material outward from the Sun that extended well beyond the Earth and into planetary space. At the same time it was also seen from observations of comets that the tails of comets were always pointing away from the Sun, with some suggestion that it could be some flow from the Sun that caused this.

It took Eugene Parker, the well-known physicist who recently passed away, to realize that there must be a wind that escaped from the Sun, and Parker showed that the wind could actually reach supersonic speeds. *In-situ* measurements by the *Ulysses* space-craft showed that during periods of quite low solar activity the solar wind had a relatively homogeneous structure, with very fast wind speeds at the poles reaching 700 kilometres per second, and slower speeds towards the equator. These speeds are significantly faster than the sound speed and also greater than that predicted by the Parker model. However, as magnetic activity increases, there is a mixing of slow and fast wind streams which makes the structure of solar outflow more complicated. So the mystery surrounding the solar wind is, how is the solar wind accelerated to these fantastic speeds? The key requirement is an additional source of momentum in the low corona, and it turns out that the addition of momentum and the heating of the corona are a related puzzle (or they appear to be at present).

The solar magnetic field plays a key role in structuring the corona, and the solar wind, but it's also also intimately linked to the heating processes that are thought to go on there. Further, flares and prominences are related to the drivers of space-weather events on Earth, and to be able to forecast or predict the space-weather events we need to understand the coronal magnetic field. Hence, there's a real need for us to understand the coronal magnetic fields, but it turns out it's very challenging to measure the magnetic field in the corona. At present, we can't really make measurements by traditional methods because the coronal magnetic field is weak and requires highly sensitive instruments. I'll discuss an alternative way we can do this.

Typically, solar observations from the Earth have been done in the visible, and this is because the Earth's atmosphere is transparent to these wavelengths and we have lots of photons coming from the Sun at these wavelengths. For X-ray and ultraviolet wavelengths, they are completely blocked out by the atmosphere. However, if we really want to study the corona, we need to focus on the infrared and look through the atmospheric windows there that enable us to take a peek at the Sun's atmosphere from the ground. If we want to measure the magnetic field from Earth, we are met with many challenges. If we try to make measurements in the optical, there is only a small Zeeman splitting in those lines. The advantages of the infrared are you have less continuum emission, so less contamination when you do coronagraph measurements; you also have less atmospheric and instrumental scattering in these types of observations and you get an increased Zeeman resolution if you are trying to make magnetic-field measurements. However, the downside is we have fewer photons coming from the Sun in these wavelengths, and there are also fewer absorption lines or emission lines to choose from to make the measurements. Hence, it's difficult to measure the coronal magnetic field except in the most intense regions. Unfortunately we can't yet launch spectropolarimeters into space that are sensitive enough to measure the coronal magnetic field.

An instrument that has made a lot of measurements of the corona in the infrared is located at Mauna Loa Solar Observatory located on Mauna Loa in Hawaii. This observatory contains an instrument called the *Coronal Multi-channel Polarimeter* (*COMP*), which is a coronagraphic spectropolarimeter. The *COMP* instrument is operated by the High Altitude Observatory, which is based in Boulder, Colorado, in the USA. *COMP* makes measurements of the corona in the 1074-nanometre [Fe XIII] line, which forms at roughly a temperature of 1·3 mega-Kelvin. *COMP* observes a second iron line at around about 1080 nanometres as well.

COMP was initially designed to try and make spectrophotometric measurements of the coronal magnetic fields, but in a bizarre twist of fate, it ended up making a fantastic discovery — the presence of Alfvénic waves in the Sun's atmosphere. MHD waves had long been predicted by Hannes Alfvén and we've seen the other varieties of MHD waves, slow and fast waves, elsewhere in the Sun's atmosphere. But Alfvén waves, which are highly incompressible waves driven by magnetic tension, are difficult to observe, mainly due to the incompatibility aspect and hence there is no modulation of intensity. However, *COMP* was able to able to measure the Doppler velocity of the infrared line. It was in these Doppler-velocity measurements that they found signatures of the elusive Alfvén waves. And in 2007 we had the first observations of Alfvén waves in the Sun's corona.

The reason we're interested in Alfvén waves is because they're one of the leading candidates for explaining the current heating problem. I want to give you a brief overview of how this Alfvénic way of heating works. The key thing is that photospheric convection can excite waves. And because the Alfvén waves are incompressible they can, in principle, propagate upwards along the magnetic fields without being subject to much damping, meaning they can make it out into the corona and solar wind. To be able to dissipate them, it turns out it's reasonably difficult but the leading theory for dissipation is based on Alfvén-wave turbulence. What happens in fluid turbulence is you inject energy at a certain spatial scale, and eddies and vortices form in the fluid, and they break that energy down. The energy is transferred to smaller and smaller spatial scales where eventually it is dissipated. Now in a fluid, this is isotropic and it happens the same in every direction. However, in a plasma the presence of a magnetic field introduces a preferred direction. The cascade of energy is suppressed along the magnetic-field direction and is predominantly perpendicular to the magnetic field, which is a key feature in Alfvénic-wave turbulence.

The discovery of Alfvénic waves was key for supporting this theory of Alfvén-wave turbulence. The picture that I outlined of Alfvén-wave propagation driven only by the granulation doesn't quite fit the observations, and this is the focus of some of my recent work. The one-dimensional velocity power spectrum obtained from measurements in the corona has a bump around about 4 mHz. This bump appears everywhere through the corona, and it's not expected from this granulation-driven picture of Alfvén waves, suggesting there's another source of Alfvén waves in the Sun's corona. This can come about through a mechanism of mode conversion and it all starts off with the acoustic mode in the Sun's interior. The acoustic modes are driven by the sub-surface convection. They spend time bouncing around the Sun's interior, and they're the ones that have been used for helioseismology and asteroseismology as well. It turns out these acoustic modes, or p-modes as they're known, can leak out from the interior along the magnetic fields. The magnetic fields provide what are called magneto-acoustic portals, allowing the p-modes to propagate into the Sun's atmosphere, and once they do they are able to mode convert. So they start off as fast acoustic waves in the interior and they mode convert to slow and fast waves, at some point in the Sun's atmosphere, where the sound speed and the Alfvén speed are equal. The fast waves from this process are then able to mode convert again close to the Sun's corona producing Alfvén waves.

The peak of the p-mode power spectrum is around about 3 mHz, close to the frequency where we see the peak of this bump in the coronal power spectrum. We haven't quite been able to finalize the connection between this mechanism and what we see in the observations, but it's currently an on-going topic of my Future Leaders fellowship. So maybe next time I speak to you, I'll be able to tell you a bit more about this process. The other exciting result that I've been involved with is that we've actually been able to measure the coronal magnetic fields by exploiting these waves. A first step in this process is that we need to be able to measure the density in the corona. It turns out that in the two infrared iron emission lines that are observed by *COMP*, the relative level population of the two lines is sensitive to the local electron density. Hence, measurements of these two infrared lines provides an estimate of the coronal electron density. The expression for the propagation speed for the Alfvénic waves depends upon the local magnetic-field strength and the local density in the atmosphere. Hence, the density measurements can be combined with the measurements of the wave speed of the Alfvén waves from *COMP*, and we did this to provide the first global map of magnetic-field strength throughout the Sun's corona. It was a really exciting result that we managed to do this; we showed that the coronal magnetic field is weak, much less than 10 gauss in many situations. This demonstrates the challenges for spectropolarimetric instruments to be able to measure this, just because it's so weak. In the future we want to take it forward and provide regular coronal magnetic-field maps, as we think it may be very useful for understanding the heating processes in the Sun, and also assisting in the prediction of space-weather drivers, such as prominences and flares.

To sum up I'd just like to describe the future of infrared observations. *COMP* has been decommissioned, unfortunately, but they're currently updating new instruments at Mauna Loa. We've also got two exciting observatories on the horizon. The first is the *Daniel K. Inouye Solar Telescope*, which is the biggest solar telescope to date. It is a four-metre-class telescope based again in Hawaii, and eventually it will have two instruments able to measure infrared emission, *DL-NIRSP* and *Cryo-NIRSP* (where the *NIRSP* stands for near-infrared spectropolarimeter). The difference from *COMP* is that these instruments will only be able to observe small regions of the Sun's corona, but will be able to do this at much higher spatial resolution. So we will have a very focussed view on these Alfvén waves and probably be able to provide very localized estimates of magnetic fields but with much more detail than we could with *COMP*. The future for coronagraphic observations is a facility called *COSMO* (*COronal Solar Magnetism Observatory*), and this is also being led by the High Altitude

Observatory. This future project is currently only in the design phase, but a key aspect is to increase vastly the size of the telescope that is used. The *COMP* instrument has only a 20-centimetre telescope and the plan for *COSMO* is for a one-and-a-half metre coronagraph. It will look much further out into the corona as well, so hopefully we'll be able to look at magnetic-field strength and wave propagation much further out from the Sun's atmosphere and tie that into the solar wind as well.

I think the future is looking bright for infrared observations, if you excuse the pun, and I'll leave it there and I'm happy to answer any questions. Thank you.

The President. Thank you very much, Richard. I can see that we have a few questions coming in, so I'm going to hand over to Sue Bowler.

Dr. Bowler. I have a question from Jeffrey Greenspan: "Although emanating from the very hot corona, solar prominences maintain a cooler temperature similar to that of the Sun's surface. How? Are the prominences somehow shielded by the magnetic fields around them?"

Dr. Morton. I'm not sure if they're shielded by the magnetic field. As you say, prominences have a lot of cool chromospheric material in them which is present from a previous cycle of plasma heating and cooling. When you have a heating event it sends energy down from, say, the corona to the chromosphere, where you get the evaporation of this chromospheric material. Along coronal loops, which have a simple magnetic field, that material just cools and drains back off again. On the other hand, for the prominences the magnetic field is twisted and there are lots of dips. The heated plasma evaporates and ends up sitting in these dips and then cools down by radiation. And so you end up with this cool material hanging in the corona just because it's stuck in dips of magnetic field. I'm pretty sure that's the general picture behind these prominences.

Dr. Bowler. Thank you, I have a question. You mentioned that you want to combine what you're finding out about the Sun up close with its effects at Earth. What do you need to do that, what sort of data does that involve?

Dr. Morton. I'm not so interested in the effects at Earth, I'm a corona boy really. But the aspects of the research that I'm interested in related to the drivers of space weather are really looking at the coronal magnetic field. The coronal magnetic field plays a role in, say, strapping these prominences down. You have overlying magnetic field above a prominence, and once that field destabilizes in some way, then the prominence is free to erupt. I'm more interested in trying to measure the magnetic-field conditions above prominences and seeing if we can identify indicators of when the prominence might erupt, for example, if the field strength starts to decrease for some reason. Providing regular magnetic-field measurements in the corona is a key aim and then hopefully this can be tied into predictive models that people are also working on.

Dr. Bowler. Thank you. That's about all we've got time for, I'm afraid, apart from one wonderful comment from Fabio F. who wanted to share some information about the *Skylab* images. He says "They were actually obtained on film, with astronauts retrieving exposed film canisters by spacewalking, and then they had to be individually scanned and analysed back on Earth." It's probably not surprising they're a bit jerky, so thank you.

The President. Thanks for reading that out Sue, and thanks again Richard, for a fantastic presentation. I really enjoyed that very much. Now we're going to move on to our next speaker this afternoon who is Dr. Matt Nicholl from the University of Birmingham, the recipient of the Fowler 'A' Award for 2022 and also a recent holder of an RAS Fellowship. Dr. Nicholl is a lecturer at the University of Birmingham and he obtained his PhD in 2015 from

Queens University, Belfast, and was then a postdoctoral fellow at the Harvard Smithsonian Centre for Astrophysics, and also a Royal Astronomical Society Research Fellow at the University of Edinburgh. He leads the ERC-funded KRANK project, which aims to understand extreme astronomical explosions with next-generation telescopes, and holds a Turing Fellowship to apply data-science techniques to improve the efficiency of detecting these rare events. So it's my great pleasure to introduce Dr. Matt Nicholl now to give his presentation entitled 'Tidal disruptions of stars by supermassive black holes'.

Dr. Matt Nicholl. We're living in a golden age for time-domain astronomy: the detection and study of explosive one-off events throughout the Universe. With current surveys like the *Zwicky Transient Facility* and the *Asteroid Terrestrial Impact Last Alert System* now finding upwards of 10 000 explosive transients per year, we've started to find some very rare events indeed.

One of the most exciting findings is a population of so-called tidal disruption events (TDEs). This is a flare caused when a star passes too close to a supermassive black hole (SMBH) in the centre of a galaxy, and is destroyed. As the star is stretched out into thin filaments, these streams wind around the SMBH and collide, releasing energy. Ultimately, this leads to a transient that rivals the brightest supernovae, and fades away over a few months.

Studying TDEs is important for many reasons. They occur in less-massive SMBHs, often in dormant galaxies, which are otherwise impossible to find. They are excellent testing grounds for General Relativity. And they are multi-messenger sources, emitting not only across the electromagnetic spectrum, but also in energetic particles and gravitational waves. However, there are many details of the disruptions we do not yet understand, including an apparent anomaly: the observed temperatures of TDEs, around 10 000 K, are around two orders of magnitude lower than expected for an accretion disc around a SMBH. This has been dubbed a 'cool photosphere'.

Over the past few years, detailed spectroscopic studies of TDEs have been making great inroads to solving this problem. The spectra of TDEs are quite diverse, with some showing hydrogen emission lines, others showing only ionized-helium lines, and some showing a mix of the two. The latter of the three groups often also show nitrogen lines. In all cases, these lines are significantly broadened, presumably by scattering in a dense medium and/or Doppler shifts indicating motion at thousands of kilometres per second.

Recently we have discovered a TDE, called AT2017eqx, that changed spectral type: from hydrogen and helium to helium-only. This can be explained if the optical light is reprocessed through an extended atmosphere that can shrink over time. In this case, hydrogen is observed in emission only in sufficiently large atmospheres; otherwise these photons are absorbed. Helium, on the other hand, emits over a much greater fraction of the atmosphere. In AT2017eqx, the radius inferred from fitting a black-body function to the spectral-energy distribution shrinks over time, from an extent expected to produce hydrogen lines to one that is too compact. This perfectly matches the evolution in the spectrum, confirming that this TDE had an extended atmosphere in which the cool photosphere can reside. This has since been confirmed statistically for a much larger sample of TDEs.

Where would such an atmosphere come from? The answer has been provided by the closest TDE to date, named AT2019qiz, occurring in a spiral galaxy only 65 Mpc away. This event has been dubbed the Rosetta Stone of TDEs because early detections at all wavelengths break some of the degeneracies that arise when interpreting the shape of the spectral-line profiles. In this case, we were able to measure an initial expansion phase while the atmosphere grew up to the time of maximum luminosity, before a period of fast cooling. Radio data also showed an expansion, proving that the shifts seen in both helium and hydrogen emission lines were due to bulk motion of matter. After the cooling phase, we were able to look deeper into this outflowing gas, and at the same time saw an increase in the luminosity of both X-ray and nitrogen emission, both of which indicate the outflow was powered by energy released as material accreted onto the SMBH. Thus, the cool photosphere in this TDE, and presumably others, forms dynamically as an accretion-driven outflow.

In other systems with accreting black holes, such as active galactic nuclei and X-ray binaries, the accretion is mediated through a rotating disc. Simulations of TDEs predict that a similar disc should form within the first few orbits of the stellar debris, but this has been difficult to confirm observationally. Data obtained years after some disruptions shows a constant luminosity indicative of a stable disc, but this does not tell us when the disc formed. Again, spectroscopy of a nearby TDE has provided a breakthrough here. AT2018hyz is a TDE that initially showed similar blue-shifted (outflow) profiles to AT2019qiz in the hydrogen Balmer lines, but within the first month this had transitioned to a complex double-peaked structure. This can be exquisitely matched by models of an inclined, circular accretion disc, showing that discs can form promptly in some TDEs, but that these can be masked behind the outflow at early times.

Together, these observations paint a picture in which a typical TDE consists of a compact accretion disc, surrounded by outflowing gas with a range of densities and velocities. This gas absorbs X-ray photons from the disc and re-emits them further out and at lower temperature, producing the apparently cool photosphere. This supports complementary efforts on the theoretical side, where hydrodynamical simulations of TDE accretion discs naturally produce these outflows. These simulations predict a possible correlation between the observed outflow velocity and X-ray brightness, since both of these should be greater in TDEs that we happen to be looking at directly face-on to the disc.

Very large samples of observed TDEs are expected over the next decade, thanks to the new *Vera Rubin Observatory* currently finishing construction in Chile. This should find 10 000 TDEs, and we can use these to look for such a correlation. Although we cannot follow every TDE in detail, the light-curves measured by *Rubin* can be compared to physical models to produce distributions of black-hole masses and other important parameters. Even with the current sample of a few tens of TDEs, we are already seeing fascinating indications that TDEs with and without hydrogen emission could arise due to differences in how close the star passes to the SMBH, and therefore where the debris streams self-collide. The future of this field is very bright indeed.

The President. Thank you so much, Matt. That was a fascinating talk and I've personally learned a lot. I'm going to hand over to Sue to see what questions we have coming in.

Dr. Bowler. I have a question from Jeff Greenspan: "Now that you've got these bigger populations, can you distinguish between different types of stars, main-sequence stars, later-stage stars, and gas clouds, and does the nature of the supermassive black hole, perhaps its spin state, have any effect on what you see?"

Dr. Nicholl. In fact, that is in some of the slides I skipped over. We can actually measure a lot of properties about the orbits and the stars from fitting models to the light-curves. This shows the three TDEs I talked about, with physical models fitted to the light-curve. You can see we got really nice fits in all the different bands here. The free parameters in this model are things like the mass of the black hole, mass of the star, how close the star passes to the black hole. It looks like there are differences between the different spectral types in the distributions of these parameters. So for example, the ones that show only hydrogen seem to come from slightly-lower-mass black holes, and they don't pass as close to the black hole as do the ones that show helium lines. So it seems that different kinds of TDEs come from different kinds of orbits around different masses of black holes. If you have a very big black hole and a very close approach, the stream wraps around much tighter and forms a disc much more quickly. Whereas if you've got a low-mass black hole or a sort of grazing encounter, the streams intersect far away from the black hole and that might make a much larger atmosphere, where we see more hydrogen emission. In terms of the masses of the stars themselves, it looks like the population is mostly consistent with low-mass main-sequence stars, but there's a slight selection effect where the smaller the star, the bigger the mass range of black holes that can disrupt it. So, it seems we're always going to be biassed towards finding quite low-mass stars with TDEs.

The President. Thanks, Sue. So, Matt, I'm just wondering, and this may not be your sort of area of study, but thinking back to Richard's talk, what role does the magnetic field of the star play, and how does that affect the interaction or indeed the debris that is taken away from the star as it passes the black hole?

Dr. Nicholl. That's a very difficult question, and the old magnetic-field angle which makes it really tricky, but I think from some of the simulations, such as this simulation here from Jane Dai, were magnetohydrodynamics simulations. So at least some of the wind driving the disc is almost certainly to do with magnetically-driven winds, but I wouldn't be able to tell you what is the relative importance of the thermal *versus* the magnetic contribution, and things like that. I think the best simulations are starting to take into account the fact that these discs should have magnetic fields, but I'm not sure what the overall impact is. Some TDEs show very clear jetted emission and even relativistic jets, and those must be magnetically collimated, I think, so those will show the strong fields.

The President. Thank you.

Dr. Bowler. We just have time for one more question. This is from Nilesh: "What's the benefit of knowing the masses of the supermassive black hole involved in these events? Might this help you plug the mass-gap in low-mass black holes?"

Dr. Nicholl. That's certainly what we're hoping. It's still not a solved problem how black holes reach the masses that they do, by early times in the Universe's history, so it's quite possible early in the Universe black holes go through eating lots of stars. If we're able to measure the mass of the black holes in all kinds of galaxies, and we're able to correlate that with the TDE rate, it might tell us a little bit about how these black holes grow. Indeed we might be able to find some intermediate-mass objects too, because those can tidally disrupt a white dwarf, and those are the ones you might see in gravitational waves in the 2030s when the *LISA* space detector is flying.

The President. We're going to move on to our third and final talk for this afternoon, which is going to be given by Professor Giovanna Tinetti from UCL, and Giovanna is the RAS Eddington Lecturer for 2022. Professor Tinetti is the head of the astrophysics group at University College London, and also director of the UCL Centre for Space Exo-chemistry Data at Harwell. She's the principal investigator of *ARIEL*, the European Space Agency's science mission to be launched in 2029. She's also co-founder of Blue Skies Space Limited, which aims at creating new opportunities for space-science satellites. She was awarded a PhD in theoretical physics from the University of Turin, Italy, in 2003. Giovanna Tinetti has continued her academic career as a NASA Astrobiology Institute Fellow at Caltech JPL, and then as a European Space Agency Fellow in Paris, before moving to UCL in 2007 as STFC Aurora, and then Royal Society URF Fellow. She has authored or co-authored over 200 research papers and has delivered over 250 talks, seminars, and public lectures internationally. So a very warm welcome to you, Giovanna, to give the Eddington Lecture today, entitled 'A chemical survey of planets in our galaxy'.

Professor Giovanna Tinetti. [It is expected that a summary of this talk will appear in a future issue of *Astronomy & Geophysics*. The Earth is special to us: it's our home. But is it really special as a planet? Every star we can see in the night sky is likely to be orbited by planets, so that there probably are a thousand billion planets in our galaxy alone. Since the discovery of the first 'exoplanet' about thirty years ago, about 5000 exoplanets have been discovered in distant solar systems, with many surprising planets and planetary systems, often very different from our own. A suite of ground-based and space telescopes are currently in operation or will be launched within this decade to discover more exciting planets and unveil their nature: What are they made of? How did they form? What's the weather like there? Are they habitable?

The *ARIEL* (*Atmospheric Remote-sensing Infrared Exoplanet Large-survey*) space telescope, to be launched in 2029 as part of the ESA Science Programme, is the first mission dedicated to the determination of the chemical composition of hundreds of exoplanets, enabling planetary science far beyond the boundaries of the Solar System. Finding out why are these new worlds as they are and what is the Earth's place in our galaxy and — ultimately — in the Universe, is one of the key challenges of modern astrophysics. The *ARIEL* mission will bring a fundamental contribution to addressing this challenge.]

The President. Giovanna, thank you so much for a fantastic talk, and it was really great to hear about the upcoming *ARIEL* mission in lots of detail. It's a very exciting future for the exoplanet field. We've got a number of questions coming through, so I'm going to hand over to Sue.

Dr. Bowler. The first one is from Jeff Greenspan: "Will *ARIEL* be able to answer the question of how a particular exoplanet's atmospheric chemistry has changed over time?"

Professor Tinetti. That's an excellent question. It is a tricky one because if you just have one object, even if you know the object with a high level of detail, it might not be easy to disentangle some of the current characteristics, whether they were caused throughout the history of the planet, but I think the great point of force of *ARIEL* is the ability of not necessarily looking at just one object, but a population of objects. Perhaps the degeneracy that we do expect when we look at one object in the right level of detail might be addressed, because if you've seen many of those objects, some of them will be similar, some would be very different. Then it's through this comparative planetology that we might be able to learn what might be due to one effect or the other, so this is what we will be planning or expecting. Whether that is true or not, I think we shall see.

Dr. Bowler. I have a question from Keith Smith, who comments that it's a very exciting mission. "There is a lot of debate about the cosmic chemical origins of atmospheres on the terrestrial planets in the Solar System, including Earth, where we have exquisite remote and *in-situ* data, including things like isotopic measurements. How well can we hope to constrain the atmospheric origin of exoplanets based only on transit spectroscopy?"

Professor Tinetti. That's an excellent question, and to a degree it is also linked with the previous one. If you just have a small number of objects, even if you have an incredible level of detail, such as happens for the planets in our Solar System, it is not granted that you can go backward and understand what happened and why they are as they are. But the hope really is that if instead of having a few, you start to have hundreds, then we will be able to see trends, and we hope to learn from these trends. For instance, I didn't show some of the simulations that we have been doing. Let us say that one sees some correlation between the presence of one molecule and the temperature of the planet or the presence of some other molecule and the type of star, and so on and so forth, then if we're seeing this sort of correlation, if we're seeing these sorts of trends, those will probably tell us something. That's where I think we might be able to learn something out of the population of planets analysed, not just individual planets.

Dr. Bowler. Thank you; I have a slightly related question from Hugh Stanley: "How is observational bias mitigated with the data obtained in these exciting missions?"

Professor Tinetti. Well, certainly it's true that *ARIEL* is using transit, a technique that is already a bias because you are biassed towards planets that are orbiting very close to the star. Otherwise the larger the orbit, the more impractical it is using transit because you need to wait too long in order to have another transit or another eclipse. So clearly there is a bias in this technique and so the idea is that at the moment you can do quite a lot with transit technique, but in the meantime of course, I mentioned direct imaging and also other observations from the ground. Ideally, we really want to use all the techniques so little by little we will be able to address all these biasses. Often with the detection of planets, you'll probably remember the diagram where we're looking at the parameter space. Not all this parameter space has been covered yet, but by using different techniques you can little by little address those biasses and the same for atmospheres. Today we can do pretty well planets that are orbiting close to the star, and when direct imaging will evolve towards being able to look at even smaller planets, then you will be able to do population studies also with direct imaging and so planets at larger distance. Hopefully by combining all these techniques, we will have a better view with less and less biasses.

Dr. Bowler. Thank you. I have a question from Paul W. who wonders: "Will *ARIEL* be capable of detecting artificial, *i.e.*, non-natural, chemicals or pollutants in atmospheres of exoplanets?"

Professor Tinetti. I'm afraid you really need a second generation of atmospheric observatories because at that point in particular, some of the species that have been considered, within our Earth's atmosphere, you need to have very small concentrations, so extremely small signals. This is not something you can do with *ARIEL* or even with *JWST* to be honest and so we really need to think of the next or even the generation following that, of exoplanet-atmosphere missions.

Dr. Bowler. Thank you, I have a question from John Fairweather: "Could Dr. Tinetti give an update on the forthcoming exoplanet satellite *Twinkle*?".

Professor Tinetti. With pleasure. *Twinkle* is a very small satellite, one of the 45-centimetre-sized satellites that we'll be launching in orbit and it will be built by Airbus. It will also be doing spectroscopic measurements in the optical and infrared, but what is new about *Twinkle* is the funding model because most space missions so far have been constructed with the funding coming from government organizations such as the European Space Agency, or NASA. This is fantastic though, don't get me wrong, but most of the time these missions, *ARIEL* here is such an example, are extremely ambitious and because of that, they're also quite expensive, and take a long time to build. It means that you can't necessarily have a mission like *ARIEL* every few years or so. You need to wait a long time and so at BSSL, which is the company that is managing *Twinkle*, we're looking into other possibilities whether we can use a different business model, a more commercial model which is required in order to be able to fund more small missions and the data from them can be accessed by the community paying a subscription. It's a little bit like the telecom type of model, but is using science data rather than telecom data if that makes sense. This is the new model that we're trying to put forward for *Twinkle*, which at the moment it is being studied by Airbus who will provide the spacecraft.

Dr. Bowler. Thank you. I have another question from Jeff Greenspan. "What considerations went into choosing to construct the *ARIEL* telescope out of aluminium?"

Professor Tinetti. Well, this was considered by the engineers who are behind the design of *ARIEL*. The spacecraft will be mainly aluminium and so you really don't want to have a different material for the telescope and the rest of the spacecraft in the payload because you want to have the thermal expansion and contraction to go together in order to have the least number possible of systematics. And so having a telescope, for instance, in silicon carbide, and then the rest of the spacecraft in aluminium would not be a good match, and so that's where we are trying to match the material for the telescope and the rest of the spacecraft and that has been a key requirement since the beginning.

Dr. Bowler. We have another question from Paul W., wondering about detecting biospheres: "I know that you said that atmospheric pollutants are going to be there in very small levels, but do we need to look at closer systems if we're going to have a chance of finding biospheres? Or are there other constraints?"

Professor Tinetti. I think we still need to understand a little bit better what a biosignature could be. We're all extremely curious to see, in particular, the first observation with *JWST* of some of these small and cold planets like the TRAPPIST-1 system that have potentially habitable environments. We don't know, of course, if they are habitable or not, and we still don't know exactly what to look for. People have put forward ideas to look for dis-equilibrium chemistry, this was the idea from Lovelock. Basically, the fact that life is creating some chemical dis-equilibrium and if you're able to look at some molecular species in the atmosphere that is completely out of equilibrium, this could be an indication that perhaps there is life on that planet, and that is a biosignature. For the Earth, the clear biosignature is the molecular oxygen or even ozone, and they are in very high concentration because of the presence of life. I think we all need to be a little bit careful when we will see all these planets, and we'll have to interpret all these spectra. You know, even planets that for sure are not habitable because they are very hot and maybe made of hydrogen, many of the atmospheres that we're looking at, even with current instrumentation, seems to show a chemistry that is out of equilibrium, and so the question is how will we be able to distinguish what is out of equilibrium because of the chemistry or because of habitability. And so I think it will be important to learn, first, what planets look like in general and hopefully, at a certain point, we'll see some planets that really stand out, and perhaps the fact that they stand out and they tick all the other boxes of habitability will tell us that maybe this information is really a biosignature, but for the moment it's very hard not to think in a too-geocentric way. I'm just very cautious when it comes to biosignatures or habitability.

The President. Thanks very much, Sue, for asking all of those questions and thank you, Giovanna, for taking the time to answer them all. Lots of interest from from our audience on your presentation. I will now close the meeting, and thank once again our excellent speakers. This afternoon we've had messages coming through, complimenting the fantastic talks; I wholeheartedly agree. Finally, I give notice that the next monthly A&G Open meeting of the Society will be on Friday the 22nd of April 2022, when we have an additional Ordinary Meeting. Thank you everybody very much for joining us this afternoon. I hope you've enjoyed it and look forward to seeing you all next time.

IS V608 CASSIOPEIAE REALLY A QUADRUPLE SYSTEM?

By Christopher Lloyd

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A recent orbital solution for V608 Cas has suggested that the system contains a W UMa binary and two similarly massive, low-luminosity companions. A re-evaluation of the eclipse timings finds that a simple third-body solution fits the data equally well, with a single companion of 0·24 $M_\odot$ in a ~23-year, modestly elliptical orbit. *TESS* data reveal large and rapid movements of the eclipses of 0·0015 days on a time-scale of 25 days.

Close binary stars are frequently found in multiple systems[1,2], with the proportion of those with close companions ranging from at least 20%[3] to about 60%[4,5] for short-period systems. Also, *Gaia* has uncovered a population of wide-binary pairs containing a W UMa binary[6]. For systems with shorter periods, measured in the tens of years, the structure tends to be more hierarchical, with companions orbiting the W UMa binary individually. The masses of these companions range from low-mass (m_3 ~ 0·15 $M_\odot$) third bodies, *e.g.*, AM Leo[7], YY Eri[8], through intermediate, *e.g.*, V523 Cas[9], and relatively high-mass (m_3 ~ 0·8 $M_\odot$) companions, *e.g.*, VW Cep[10], ER Ori[11], to quadruple systems with two binaries, *e.g.*, TZ Boo, V2610 Oph[2].

In most systems where an eclipsing binary has a companion it is detected through the orbital motion it imparts to the binary, and this appears as a vaguely sinusoidal variation in the residuals in the O–C diagram due to the light-travel-time effect (LTTE). How sinusoidal this variation is depends on the eccentricity of the third-body orbit, and if there are other companions then the variation can become quite complex. In addition, if there is a secular change in the period of the eclipsing binary then that will superimpose an extra parabolic term on the residuals, which in the long term will dominate the cyclical variations of any companions. In relatively short runs of data there may be some uncertainty about which effects dominate, and in complex systems it can take several orbits of any companions before the true picture emerges.

V608 Cas is a 12th-magnitude, neglected, but fairly average, W UMa system with $P = 0^{d}{\cdot}38$, but it has total eclipses, both $\sim 0^{m}{\cdot}5$ deep, so is potentially interesting. The variation was discovered by Hübel[12] but the first light-curves were not made until about 25 years later by Cook[13] and Blättler & Diethelm[14], and it has only been observed actively for the last decade. There have been three recent photometric studies: Liu *et al.*[15], Panpiboon *et al.*[16], and Park & Lee[17], and they suggest that the system is mildly overcontact with a fill-out factor of 20–25%, and a mass ratio of $q \sim 0{\cdot}33$, with $m_1 = 0{\cdot}9$ and $m_2 = 0{\cdot}3\ M_{\odot}$. The temperature of the system is estimated from the colours as $T_{\rm eff} \sim 5400 \pm 250$ K, and opinions differ on whether the secondary is hotter or not, but clearly there is little difference. The system shows an intermittent O'Connell effect which requires photometric models with cool spots on the primary from Liu *et al.* and Panpiboon *et al.*; however, the system changes quickly as Park & Lee's solution does not require spots but does favour the inclusion of a third light of 8% in *V* and 5% in *R*.

Although the data are limited it is clear that the period of V608 Cas is variable. Period studies by Liu *et al.* and Panpiboon *et al.* show a poorly sampled but clear parabolic run of residuals in the O–C diagram that has been interpreted as a period change of $dP/dt = +0{\cdot}034(4)$ seconds/year, which is about equivalent to the 1-σ point of the W UMa distribution[3]. However, using more data, Park & Lee suggest that in addition to the secular period change, the W UMa binary has two circumbinary companions. The light-travel times for these are large for this type of system at $\sim 0^{d}{\cdot}034$ for both companions, leading to minimum masses of 2·1 and 1·3 $M_{\odot}$, both of which are more massive than the central binary. In addition to raising dynamical and evolutionary issues, both stars should add enormously to the luminosity of the system, but from their photometric modelling of the light-curve Park & Lee limit any third-light contribution to 5–8%. As they point out, their two companions would have to be relatively massive, low-luminosity objects. These are very different to others that have been proposed in W UMa binaries, so they deserve to be re-investigated.

Park & Lee[17] provide a comprehensive list of previously published times of minima plus some measurements of their own. The other major set of timings comes from Liu *et al.* but the values from their individual light-curves are used here as opposed to the averaged values. Some previously published times of minima not used or unavailable to Park & Lee have been taken from the collections of the O–C Gateway* and the BAV Lichtenknecker-Database†. In addition, new times of minima are measured from photometry of V608 Cas in the AAVSO International Database‡, including the early set of observations by Cook[13]. For Cook's data the time of primary and secondary minimum were calculated using a 4-harmonic Fourier fit to the folded light-curve and although it is not well observed it does provide the first eclipse timing. For all the other AAVSO data the minima were derived from individual light-curves using the Kwee–van Woerden method[18]. The other early data set comes from the Northern Variability Sky Survey (NSVS)[19] and provides composite timings, again using a 4-harmonic Fourier fit.

* http://var2.astro.cz/ocgate/

† https://bav-astro.eu/index.php/veroeffentlichungen/service-for-scientists/lkdb-engl

‡ https://www.aavso.org/aavso-international-database-aid

Further data are available from the All-Sky Automated Survey for Supernovae (ASAS-SN), the *Zwicky Transient Facility* (*ZTF*), and the *Asteroid Terrestrial-Impact Last Alert System* (*ATLAS*) synoptic surveys. ASAS-SN observations[20,21] are typically made in groups of three in the space of $0^{d}{\cdot}003$ (4 minutes), and measurements have been taken from the direct aperture-photometry pipeline of the individual images. Seasonal composite timings have been derived using a 4-harmonic Fourier fit from 2015–2018 in *V*, and 2018–2021 in Sloan *g*. *ZTF* data[22] are available from 2018 to the present in the *zg* band and seasonal composite timings have been derived using a 4-harmonic Fourier fit. Data from the *ATLAS*[23,24] project are typically made in groups of four over about an hour in the cyan and orange bands. Observations were downloaded from the *ATLAS* Forced Photometry Server using the simple-aperture-photometry option and seasonal composite timings derived as above for 2015–2021, using just the orange-band data. For all these data sets, and the AAVSO and NSVS data, the times of minima have been calculated from the original UTC or JD dates as appropriate and the heliocentric corrections calculated using the Terrestrial Time (TT) date, which for the avoidance of confusion include the TAI – UT1 offset of 32·184 seconds and the appropriate number of leap seconds. These values have been compared to their BJD_{TDB} equivalents using the routines of Eastman *et al.*[25] and agree within a few seconds, as they should. Not all HJDs are created the same; see the discussion at the end of their paper. See also their on-line utilities*.

The most important new observations come from the *Transiting Exoplanet Survey Satellite* (*TESS*) which observed the system in Sectors 18, 19, 25, and 52, in 2019, 2020, and most recently in 2022 May. The *TESS* photometry was obtained at the 120-s short cadence and provides the most precise and extensive data currently available. V608 Cas is an isolated object and suffers no significant contamination by nearby stars. The raw data were downloaded from the MAST archive† and reduced using the LIGHTKURVE package[26]. The data were restricted to HARD quality in LIGHTKURVE parlance, which in this case used only the best data with QUALITY flag zero, and the fluxes were measured using the default aperture generated by LIGHTKURVE. The resulting light-curve is remarkably flat in the sense that no additional polynomial fitting is required to correct the level through the *TESS* orbit, as is often the case. A few cycles of the binary were rejected from the start of Sector 18 as these were clearly at odds with the rest of the data. The *TESS* sectors naturally divide into two due to the 1–2-day break for the data downlink, so the resulting light-curve comprises eight sections of about 11 days of mostly continuous data. Sector 25 has more severe problems with the background and the greatest data rejection, but these runs still contain over 6000 data points while the others each have typically 7000–8000 points. The phase diagram of Sectors 18 and 19 is given in Fig. 1 and shows two nearly equal eclipses $0^{m}{\cdot}528$ and $0^{m}{\cdot}495$ deep. Primary eclipse is broader and clearly total, with the secondary less obviously so. The data in the secondary minimum are also less tightly constrained than in the primary for reasons that will be discussed later. There is a clear but weak O'Connell effect of $0^{m}{\cdot}01$[27,28].

Another important, but far from obvious, feature of Fig. 1 is that primary minimum is not the same eclipse as the one identified in the photometric models. In all of these the broader and clearly total eclipse is identified as the secondary, and for Park & Lee's solution their secondary eclipse is actually

*https://astroutils.astronomy.osu.edu/time/

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

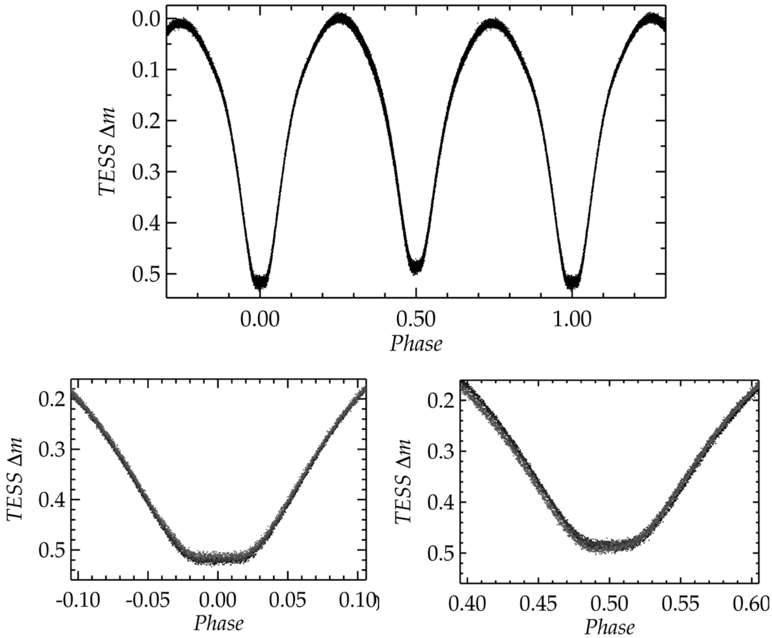

FIG. 1

Phase diagram of the *TESS* data from Sectors 18 and 19, with the detail around primary and secondary minimum. Both eclipses are total with the primary being slightly deeper and broader. There is a clear but weak O'Connell effect. The greater dispersion of the data around the secondary eclipse can be seen in both the full and detail plots, and it may be possible to see the movement of the secondary eclipse as the earlier (darker) points migrate from the inside (on the ingress) to the outside of the eclipse (on the egress) as the secondary eclipse becomes earlier.

the deeper one. For Panpiboon *et al.*'s solution the identification of the deeper eclipse is ambiguous depending on the data set (see their Fig. 3), but Liu *et al.*'s solution usually identifies the narrower eclipse as the deeper one (see their Fig. 4). Both Liu *et al.* and Panpiboon *et al.* had to introduce spots to account for the difference in the brightness of the alternate maxima, but what was not mentioned was that they were modelling the negative O'Connell effect, which is unusual and also suggests a misidentification of the minima. The implication of this is that all the published eclipse timings refer to the wrong minimum and the assumptions that have gone into the photometric models need to be reconsidered.

Before discussing the LTTE solution it is necessary to revisit the *TESS* data. Timings for 447 individual minima have been measured using the Kwee–van Woerden method and while the statistical uncertainty is typically $0^{\mathrm{d}}\cdot00008$, there are coherent and significant changes in the relationship between the primary and secondary eclipses of up to $0^{\mathrm{d}}\cdot001$, and a displacement of the two eclipses by as much as $0^{\mathrm{d}}\cdot0015$. The O–C diagrams of the four sectors are shown in Fig. 2 and are constructed relative to the LTTE solution determined later. For Sectors 18 and 19 the primary period is relatively constant but the secondary flips from a similar period to a shorter one, and then back again in about 25 days, during which time the O–C value changes from +0·0005 to –0·0010. The movement of the secondary eclipse can be seen in the phase

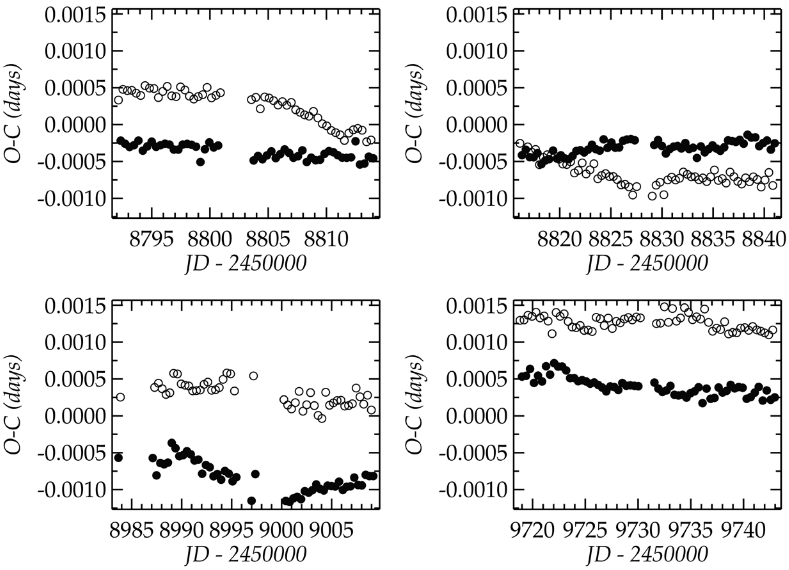

Fig. 2

The O–C diagram of the 447 individual *TESS* minima from Sectors 18 and 19 (top), and Sectors 25 and 53 (bottom). The timings are plotted relative to the LTTE solution so the absolute values are not fixed, and as the *TESS* data were weighted almost equally to the other points, this probably accounts for the positioning of Sector 53. It is the relative timings that are important. Filled symbols are primary minima and open symbols show the secondary.

diagram in Fig. 1 as an increase in spread of the data, and it may be possible to see the earlier (darker) points migrate from the inside (on the ingress) to the outside of the eclipse (on the egress) as the secondary eclipse becomes earlier. For Sector 25 the primary eclipse shows more variability but the secondary is clearly not constant. However, there is a large and variable difference in the timing of the eclipses reaching $0^{d}{\cdot}0015$. During Sector 53 both eclipses have relatively constant but slightly different periods, but maintain a displacement in excess of $0^{d}{\cdot}0007$.

Mean times of minima have been measured for each of the eight half-sectors and these are collected together with all the other timings used in Table I. The *TESS* timings are strictly BJD_{TDB} but this is at most four seconds from HJD and in view of the large movement of the eclipses no attempt has been made to transform the other timings. Having revised the previous assignments of the published minima the observed times are fitted to the standard linear form of the ephemeris for the eclipsing binary, plus the offset due to the light-travel-time effect (LTTE) of the companion, so

$$\mathrm{HJD}_k = T_0 + P_0 C_k + \tau_k, \qquad (1)$$

where T_0 and P_0 are the epoch zero and period of the eclipsing binary, C_k is the cycle number at minimum k, and τ_k is the LTTE offset at minimum k for the third body. The LTTE expression given by Irwin[29,30] has been used here, where

TABLE I

Times of minimum

HJD	*Error*	*Min.*	*Cycle*	*O–C (d)* *Linear*	*O–C (d)* *LTTE*	*Band*	*Observer/Source*
2450741·6773	0·0024	2	−21174·5	0·0068	−0·0015	*V*	Cook (This paper)
2450769·6410	0·0020	1	−21101·0	0·0109	0·0026	*V*	Cook (This paper)
2451459·4963	0·0005	2	−19287·5	0·0054	−0·0006	*R*	NSVS (This paper)
2451459·6867	0·0005	1	−19287·0	0·0056	−0·0004	*R*	NSVS (This paper)
2451926·4397	0·0009	1	−18060·0	0·0041	0·0002	*C*	Blättler & Diethelm[14]
2452001·3790	0·0008	1	−17863·0	0·0040	0·0005	*C*	Blättler & Diethelm[14]
2452041·5100	0·0008	2	−17757·5	0·0025	−0·0008	*C*	Blättler & Diethelm[14]
2452058·4387	0·0007	1	−17713·0	0·0033	0·0001	*C*	Blättler & Diethelm[14]
2452065·4768	0·0009	2	−17694·5	0·0039	0·0008	*C*	Blättler & Diethelm[14]
2454071·3191[†]	0·0024	2	−12421·5	−0·0187	−0·0118	*C*	U. Schmidt (Hübscher & Walter[33])
2454812·7353	0·0005	2	−10472·5	−0·0079	0·0009	*V*	Diethelm[34]
2455100·8897	0·0006	1	−9715·0	−0·0087	0·0002	*V*	Diethelm[35]
2455170·6927	0·0002	2	−9531·5	−0·0097	−0·0008	*C*	Nelson[36]
2455473·3031	0·0016	1	−8736·0	−0·0098	−0·0016	*C*	F. Agerer (Hübscher[37])
2455473·4952	0·0021	2	−8735·5	−0·0079	0·0003	*C*	F. Agerer (Hübscher[37])
2455542·7275	0·0002	2	−8553·5	−0·0090	−0·0009	*V*	Diethelm[38]
2455804·4469	0·0006	2	−7865·5	−0·0068	0·0001	*C*	F. Agerer (Hübscher & Lehmann[39])
2455850·8534	0·0006	2	−7743·5	−0·0095	−0·0028	*V*	Diethelm[40]
2456155·5615	0·0002	2	−6942·5	−0·0042	0·0004	*R*	Hoňková *et al.*[41]
2456203·8719	0·0003	2	−6815·5	−0·0049	−0·0008	*V*	Diethelm[42]
2456226·12661	0·00053	1	−6757·0	−0·0038	0·0002	*V*	Liu *et al.*[15]
2456226·12737	0·00041	1	−6757·0	−0·0031	0·0010	*Ic*	Liu *et al.*[15]
2456226·12805	0·00036	1	−6757·0	−0·0024	0·0016	*Rc*	Liu *et al.*[15]
2456226·31722	0·00038	2	−6756·5	−0·0034	0·0006	*Rc*	Liu *et al.*[15]
2456226·31747	0·00052	2	−6756·5	−0·0032	0·0009	*Ic*	Liu *et al.*[15]
2456226·31778	0·00054	2	−6756·5	−0·0028	0·0012	*V*	Liu *et al.*[15]
2456288·13195	0·00037	1	−6594·0	−0·0042	−0·0007	*Ic*	Liu *et al.*[15]
2456288·13216	0·00065	1	−6594·0	−0·0039	−0·0004	*V*	Liu *et al.*[15]
2456288·13247	0·00041	1	−6594·0	−0·0036	−0·0001	*Rc*	Liu *et al.*[15]
2456289·08354	0·00075	2	−6591·5	−0·0036	−0·0001	*V*	Liu *et al.*[15]
2456289·08420	0·00036	2	−6591·5	−0·0029	0·0006	*Ic*	Liu *et al.*[15]
2456289·08464	0·00054	2	−6591·5	−0·0025	0·0010	*Rc*	Liu *et al.*[15]
2456290·03505	0·00038	1	−6589·0	−0·0031	0·0004	*Ic*	Liu *et al.*[15]
2456290·03507	0·00048	1	−6589·0	−0·0031	0·0004	*V*	Liu *et al.*[15]
2456290·03703	0·00033	1	−6589·0	−0·0011	0·0024	*Rc*	Liu *et al.*[15]
2456549·28051	0·00030	2	−5907·5	−0·0022	−0·0011	*Ic*	Liu *et al.*[15]
2456549·28088	0·00036	2	−5907·5	−0·0019	−0·0007	*Rc*	Liu *et al.*[15]
2456549·28113	0·00030	2	−5907·5	−0·0016	−0·0004	*N*	Liu *et al.*[15]
2456602·15712	0·00039	2	−5768·5	−0·0016	−0·0010	*Rc*	Liu *et al.*[15]
2456602·15726	0·00025	2	−5768·5	−0·0015	−0·0008	*N*	Liu *et al.*[15]
2456602·15728	0·00044	2	−5768·5	−0·0015	−0·0008	*Ic*	Liu *et al.*[15]
2456629·16667	0·00020	2	−5697·5	−0·0007	−0·0003	*Ic*	Liu e*et al.*[15]
2456629·16678	0·00010	2	−5697·5	−0·0006	−0·0002	*N*	Liu *et al.*[15]
2457007·6716	0·0002	2	−4702·5	0·0033	0·0003	*C*	Nelson[43]
2457016·03987	0·00020	2	−4680·5	0·0027	−0·0003	*Ic*	Liu e*et al.*[15]
2457016·03995	0·00018	2	−4680·5	0·0027	−0·0003	*Rc*	Liu *et al.*[15]
2457254·9347	0·0001	2	−4052·5	0·0044	−0·0004	*C*	Nelson[44]
2457333·86915	0·00033	1	−3845·0	0·0053	−0·0001	*V*	ASAS-SN (This paper)
2457334·05891	0·00028	2	−3844·5	0·0048	−0·0006	*V*	ASAS-SN (This paper)
2457363·73151	0·00013	2	−3766·5	0·0060	0·0004	*V*	E.V. Dose (This paper)
2457383·5114	0·0001	2	−3714·5	0·0049	−0·0008	*C*	U. Schmidt (Hübscher[45])
2457622·78618	0·00024	2	−3085·5	0·0062	−0·0008	*V*	E.V. Dose (This paper)
2457694·87448	0·00039	1	−2896·0	0·0082	0·0008	*V*	ASAS-SN (This paper)
2457695·06511	0·00038	2	−2895·5	0·0086	0·0012	*V*	ASAS-SN (This paper)
2457989·4971	0·0001	2	−2121·5	0·0087	0·0003	*C*	F. Agerer (Pagel[46])
2458025·82490	0·00047	1	−2026·0	0·0080	−0·0005	*V*	ASAS-SN (This paper)
2458026·01606	0·00049	2	−2025·5	0·0090	0·0005	*V*	ASAS-SN (This paper)
2458050·74292	0·00023	2	−1960·5	0·0096	0·0011	*V*	E.V. Dose (This paper)
2458066·90911	0·00050	1	−1918·0	0·0087	0·0001	*o*	*ATLAS* (This paper)
2458067·09909	0·00044	2	−1917·5	0·0085	−0·0001	*o*	*ATLAS* (This paper)
2458116·74211	0·00015	1	−1787·0	0·0089	0·0003	*V*	E.V. Dose (This paper)
2458343·4613	0·0007	1	−1191·0	0·0079	−0·0010	*C*	F. Agerer (Pagel[47])

TABLE I (Continued)

Times of minimum

HJD	*Error*	*Min.*	*Cycle*	*O–C (d) Linear*	*O–C (d) LTTE*	*Band*	*Observer/Source*
2458373·5128	0·0008	1	−1112·0	0·0076	−0·0013	*C*	F. Agerer (Pagel[47])
2458381·88740	0·00103	1	−1090·0	0·0133	0·0044	*V*	ASAS-SN (This paper)
2458382·07444	0·00093	2	−1089·5	0·0102	0·0012	*V*	ASAS-SN (This paper)
2458389·87157	0·00014	1	−1069·0	0·0090	0·0001	*V*	E.V. Dose (This paper)
2458403·56574	0·00069	1	−1033·0	0·0087	−0·0002	*zg*	*ZTF* (This paper)
2458403·75738	0·00077	2	−1032·5	0·0101	0·0012	*zg*	*ZTF* (This paper)
2458420·68459	0·00027	1	−988·0	0·0094	0·0005	*V*	E.V. Dose (This paper)
2458420·87592	0·00022	2	−987·5	0·0105	0·0016	*V*	E.V. Dose (This paper)
2458440·4585†	0·0001	1	−936·0	0·0024	−0·0066	*C*	U. Schmidt (Pagel[47])
2458440·6483†	0·0001	2	−935·5	0·0020	−0·0070	*C*	U. Schmidt (Pagel[47])
2458453·01922	0·00031	1	−903·0	0·0098	0·0009	*o*	*ATLAS* (This paper)
2458453·20851	0·00038	2	−902·5	0·0089	−0·0001	*o*	*ATLAS* (This paper)
2458460·05588	0·00008	2	−884·5	0·0090	0·0001	*V*	Park & Lee[17]
2458461·00690	0·00010	1	−882·0	0·0090	0·0001	*V*	Park & Lee[17]
2458478·88531	0·00030	1	−835·0	0·0085	−0·0005	g	ASAS-SN (This paper)
2458479·07632	0·00032	2	−834·5	0·0093	0·0004	g	ASAS-SN (This paper)
2458716·82724	0·00018	2	−209·5	0·0083	−0·0004	*V*	E.V. Dose (This paper)
2458793·09686	0·00070	1	−9·0	0·0072	−0·0015	*o*	*ATLAS* (This paper)
2458793·28738	0·00080	2	−8·5	0·0075	−0·0012	*o*	*ATLAS* (This paper)
2458793·85823	0·00064	1	−7·0	0·0077	−0·0009	*zg*	*ZTF* (This paper)
2458794·04909	0·00056	2	−6·5	0·0084	−0·0003	*zg*	*ZTF* (This paper)
2458796·521594	0·000012	1	0·0	0·0083	−0·0004	*C*	*TESS* (This paper)
2458796·712518	0·000012	2	0·5	0·0090	0·0003	*C*	*TESS* (This paper)
2458801·84834	0·00026	1	14·0	0·0094	0·0007	g	ASAS-SN (This paper)
2458802·03778	0·00030	2	14·5	0·0086	−0·0000	g	ASAS-SN (This paper)
2458808·885049	0·000013	2	32·5	0·0086	−0·0000	*C*	*TESS* (This paper)
2458809·074738	0·000013	1	33·0	0·0081	−0·0005	*C*	*TESS* (This paper)
2458822·008495	0·000010	1	67·0	0·0082	−0·0004	*C*	*TESS* (This paper)
2458822·198449	0·000011	2	67·5	0·0079	−0·0007	*C*	*TESS* (This paper)
2458835·131980	0·000014	2	101·5	0·0078	−0·0008	*C*	*TESS* (This paper)
2458835·322650	0·000011	1	102·0	0·0082	−0·0004	*C*	*TESS* (This paper)
2458840·64760	0·00032	1	116·0	0·0075	−0·0011	*V*	E.V. Dose (This paper)
2458840·83738	0·00021	2	116·5	0·0071	−0·0015	*V*	E.V. Dose (This paper)
2458884·96524	0·00007	2	232·5	0·0082	−0·0003	*V*	Park & Lee[17]
2458913·68608	0·00017	1	308·0	0·0086	0·0002	*V*	E.V. Dose (This paper)
2458991·098062	0·000019	2	511·5	0·0086	0·0003	*C*	*TESS* (This paper)
2458991·287183	0·000024	1	512·0	0·0075	−0·0008	*C*	*TESS* (This paper)
2459004·411917	0·000025	2	546·5	0·0084	0·0001	*C*	*TESS* (This paper)
2459004·600957	0·000018	1	547·0	0·0072	−0·0011	*C*	*TESS* (This paper)
2459095·71087	0·00024	2	786·5	0·0106	0·0026	*V*	E.V. Dose (This paper)
2459095·89782	0·00016	1	787·0	0·0074	−0·0007	*V*	E.V. Dose (This paper)
2459143·06828	0·00088	1	911·0	0·0078	−0·0001	*o*	*ATLAS* (This paper)
2459143·25933	0·00074	2	911·5	0·0087	0·0008	*o*	*ATLAS* (This paper)
2459147·06264	0·00101	2	921·5	0·0080	0·0001	*V*	Park & Lee[17]
2459149·53439	0·00072	1	928·0	0·0071	−0·0008	*zg*	*ZTF* (This paper)
2459149·72471	0·00077	2	928·5	0·0072	−0·0007	*zg*	*ZTF* (This paper)
2459164·75134	0·00022	1	968·0	0·0079	0·0001	*g*	ASAS-SN (This paper)
2459164·94198	0·00026	2	968·5	0·0084	0·0005	*g*	ASAS-SN (This paper)
2459192·13997	0·00018	1	1040·0	0·0075	−0·0002	*V*	Park & Lee[17]
2459238·54948	0·00021	1	1162·0	0·0079	0·0003	*I*	R.E. Schmidt (This paper)
2459243·49438	0·00011	1	1175·0	0·0076	−0·0001	*I*	R.E. Schmidt (This paper)
2459249·96141	0·00013	1	1192·0	0·0077	0·0001	*V*	Park & Lee[17]
2459515·86177	0·00024	1	1891·0	0·0064	−0·0003	*g*	ASAS-SN (This paper)
2459516·05245	0·00026	2	1891·5	0·0069	0·0002	*g*	ASAS-SN (This paper)
2459539·06627	0·00038	1	1952·0	0·0063	−0·0003	*o*	*ATLAS* (This paper)
2459539·25566	0·00074	2	1952·5	0·0055	−0·0011	*o*	*ATLAS* (This paper)
2459724·513473	0·000014	2	2439·5	0·0071	0·0012	*C*	*TESS* (This paper)
2459724·702876	0·000014	1	2440·0	0·0063	0·0004	*C*	*TESS* (This paper)
2459737·255952	0·000013	1	2473·0	0·0061	0·0002	*C*	*TESS* (This paper)
2459737·447079	0·000015	2	2473·5	0·0070	0·0012	*C*	*TESS* (This paper)

† not used in the solution

the light-travel time for the companion is given by,

$$\tau_k = A[(\cos E_k - e)\sin\omega + (1 - e^2)^{1/2}\sin E_k \cos\omega], \qquad (2)$$

where E_k is the eccentric anomaly at minimum k, e is the orbital eccentricity, ω is the argument of periastron, and A is the semi-amplitude of the light-travel time of the orbit of the close-binary pair in reaction to the motion of the third body. The light-travel time, $A = a_{12}\sin i/c$, where $a_{12}\sin i$ is the projected semi-major axis of the orbit of the central binary.

For the fitting there are two issues that need to be considered. The first is that the data barely cover one cycle of the third body so care needs to be taken to determine if this is even constrained. The second issue is the weighting of the data. The relative weights cover an enormous range, but the natural weights obviously cannot be used as the *TESS* data have shown that the real uncertainties are dominated by the movement of the eclipses. The results of various weighting schemes produced very similar solutions but ultimately it was decided to limit the weights to the equivalent of an error of $0^{\mathrm{d}}.009$ as this leads to $\chi^2_\nu \approx 1$, and should provide the most realistic values of the error on the solution. In fact, apart from the effect of a small number of low-weight points this solution is essentially the same as an unweighted one. It was decided not to scale the errors to produce the same result as this preserves the relative weighting, which is not what is wanted. Circular and eccentric solutions were derived and for all weighting schemes the eccentric solution is a significantly better fit. For the adopted scheme the reduced chi-squared, χ^2_ν, is 1·205 and 1·003 for the circular and elliptical orbits, respectively, leading to a significant improvement at better than 0·01% according to the *F*-test.

The resulting solution is shown in Fig. 3 for the eccentric orbit and the parameters are given in Table II for this and the circular orbit for comparison. The solution has $P_3 = 8238 \pm 513$ days (22·6 ± 1·4 years), and despite the lack of coverage this quantity is robust against being pushed towards higher values. Solutions with P_3 fixed progressively up to 20000 days generate increasing values of χ^2_ν. The amplitude of the light-travel time is 0·0089 ± 0·0005 days, which is typical of third bodies in these systems. The eccentricity $e = 0{\cdot}27 \pm 0{\cdot}06$, is modest but this value should be regarded as provisional until a full cycle has been covered. The residuals from the fit, which are shown in the lower panel of Fig. 3, show no obvious trends that might indicate a secular period change or

TABLE II

Light-travel-time solution

Parameter		*Circular orbit*	*Elliptical orbit*	
T_0	=	2458796·51346(39)	2458796·51333(63)	HJD
P_0	=	0·380403102(45)	0·380402975(107)	d
A	=	0·00901(36)	0·00892(52)	d
e	=	0·0 (fixed)	0·266(56)	
ω	=	0·0 (fixed)	−9 ± 8	°
T_3	=	2456619 ± 29	2456525 ± 167	JD
P_3	=	7557 ± 184	8238 ± 513	d
χ^2_v	=	1·205	1·003	
$a_{12}\sin i$	=	1·55(6)	1·54(9)	AU
$f(\mathrm{m})$	=	0·00882	0·00720	$M_\odot$
$m_3\sin i$	=	0·26	0·24	$M_\odot$
K_{12}	=	2·2	2·1	km s^{-1}

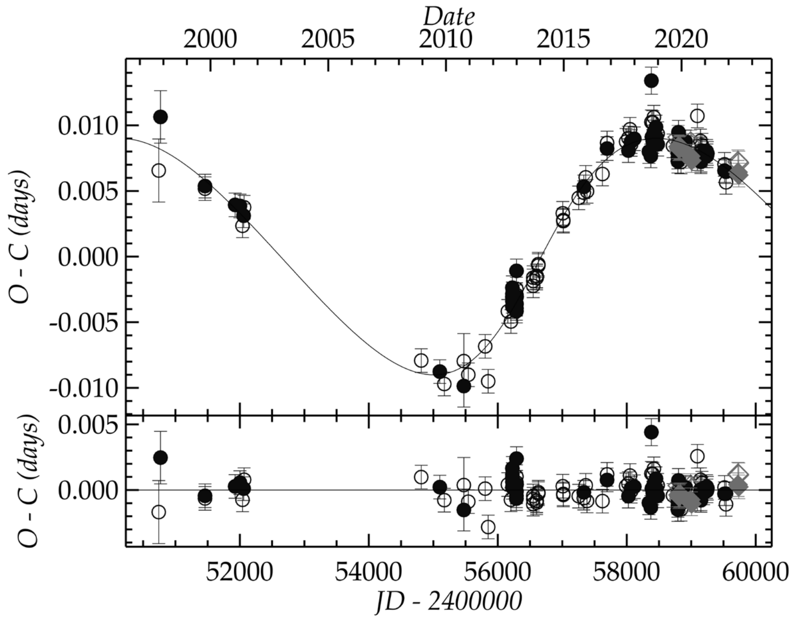

FIG. 3

The O–C diagram of V608 Cas showing the elliptical third-body light-travel-time solution. The error bars reflect the values used in the solution and are not the measured uncertainties as given in Table I. The diamonds identify the *TESS* data. Filled symbols are primary minima and open symbols show the secondary.

another companion. For completeness, a search for the the quadratic term of the ephemeris was made and it was found to be insignificant at $dP/dt = 0{\cdot}0021 \pm 0{\cdot}0014$ seconds/year, but given that P_3 is poorly determined, dP/dt will also be unreliable.

Derived parameters of the system have been calculated from the well-known expressions for the mass function (see *e.g.*, Hilditch[31]),

$$f(m) = \frac{4\pi^2}{GP_3^2}(a_{12}\sin i_3)^3 = \frac{(m_3 \sin i_3)^3}{(m_{12}+m_3)^2} = \frac{(1-e_3^2)^{3/2}}{2\pi G} P_3 K_{12}^2, \qquad (3)$$

where m_{12} is the mass of the close-binary pair, m_3 is the mass of the third body, a_{12} is the semi-major axis of the binary pair in the third-body orbit, and K_{12} is the velocity semi-amplitude of the binary pair in reaction to the third body. The other constants have their usual meaning. Taking the total mass of the binary as $m_{12} = 1{\cdot}2\ M_\odot$[15,17] then the minimum mass of the third body is $m_3 = 0{\cdot}24\ M_\odot$, and well within the range of companions seen in similar systems. From the Rochester calibration (see Pecaut & Mamajek[32]) a star of this mass has $\log L = -2{\cdot}1\ L_\odot$, compared with $\log L = -0{\cdot}05$ of the W UMa binary from the photometric solutions[15–17]. On this basis the third component would contribute $< 1\%$ to the luminosity of the system and is unlikely to be visible.

An attempt was made to replicate Park & Lee's complex solution but the data are now not identical as some timings (not just the assignment) have been revised, and some new data added. The most challenging additions are the recent *TESS* timings as these extend the data into a particularly complex region of their fit. The times of minimum are now fitted to the quadratic form of the ephemeris for the eclipsing binary, to account for the linear period change, plus offsets due to the light-travel-time effect (LTTE) of both companions, so

$$\mathrm{HJD}_k = T_0 + P_0 C_k + aC_k^2 + \tau_{k,3} + \tau_{k,4} \qquad (4)$$

where a is the quadratic term, and $\tau_{k,3}$ and $\tau_{k,4}$ are the LTTE offsets at minimum k for the third and fourth bodies, as given in Equation 2.

Using Park & Lee's solution for the initial parameters it is possible to fit a secular period change plus two LTTE components to the data, but the solution is fragile as P_4 exceeds the time span of the data, and the two large LTTE terms $A_{3,4}$ operate against each other to limit the variation to what is seen in the O–C diagram (see Fig. 4). The important parameters are all consistent with Park & Lee's solution with $P_3 = 17{\cdot}3 \pm 0{\cdot}5$ and $P_4 = 28{\cdot}8 \pm 12{\cdot}3$ years, $e_3 = 0{\cdot}53 \pm 0{\cdot}09$ and $e_4 = 0{\cdot}61 \pm 0{\cdot}10$, $A_3 = 0{\cdot}037 \pm 0{\cdot}008$, and $A_4 = 0{\cdot}040 \pm 0{\cdot}012$ days, but the uncertainties given here are considerably larger as the weighting scheme is different to Park & Lee's. Ultimately the complex solution does not provide a significantly better fit as $\chi^2_\nu = 1{\cdot}070$ is larger than the simple solution, so there is no justification for using it. Such a complex solution is only possible because the O–C diagram is so under-sampled, and while the dominant time-scale of the variation is ~ 20 years, only about half of this is well covered and a large section is unconstrained. Park & Lee were driven in the direction of this solution by

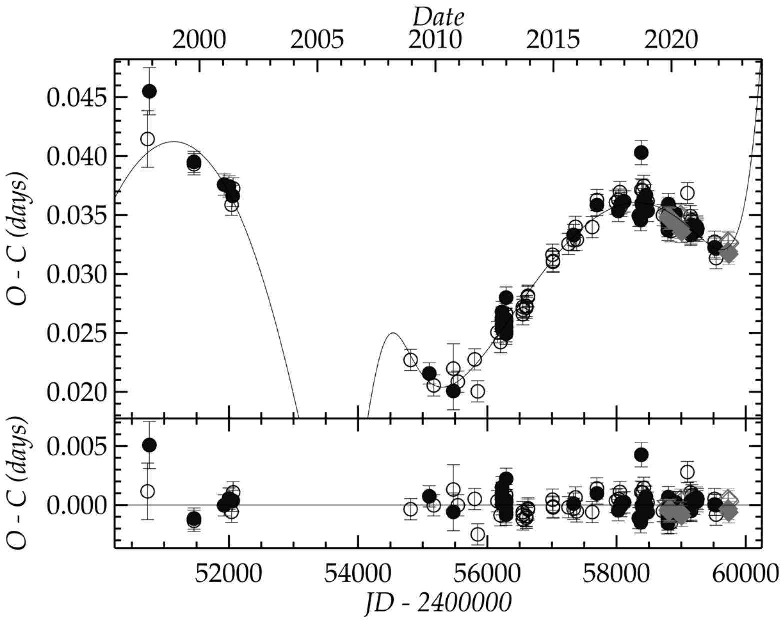

Fig. 4

The O–C diagram of V608 Cas showing the recalculated Park & Lee, two-component-plus-secular change, light-travel-time solution. The data are the same as in Fig. 4 and the symbols are as before.

earlier papers assuming a secular period change on the basis of the limited data available at the time. With more data it is now possible to recognize that the dominant variation is more likely sinusoidal than secular.

In conclusion V608 Cas appears to be an average W UMa system with a third body of minimum mass $m_3 = 0{\cdot}24\ M_{\odot}$ in a 23-year orbit of modest eccentricity. More observations are required to define better the period and eccentricity. The data do not require, and are not significantly better fitted by, a more complex solution. The possible surprise is the scale and speed of the variation of the eclipse timings, which has implications for other W UMa systems, particularly if this star is average for the class.

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REDISCUSSION OF ECLIPSING BINARIES. PAPER 11: ZZ URSAE MAJORIS, A SOLAR-TYPE SYSTEM SHOWING TOTAL ECLIPSES AND A RADIUS DISCREPANCY

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ZZ UMa is a detached eclipsing binary with an orbital period of 2·299 d that shows total eclipses and starspot activity. We used five sectors of light-curves from the *Transiting Exoplanet Survey Satellite* (*TESS*) and two published sets of radial velocities to establish the properties of the system to high precision. The primary star has a mass of 1·135 ± 0·009 $M_\odot$ and a radius of 1·437 ± 0·007 $R_\odot$, whilst the secondary component has a mass of 0·965 ± 0·005 $M_\odot$ and a radius of 1·075 ± 0·005 $R_\odot$. The properties of the primary star agree with theoretical predictions for a slightly super-solar metallicity and an age of 5·5 Gyr. The properties of the secondary star disagree with these and all other model predictions: whilst the luminosity is in good agreement with models the radius is too large and the temperature is too low. These are the defining characteristics of the *radius discrepancy* which has been known for 40 years but remains an active area of research. Starspot activity is evident in the out-of-eclipse portions of the light-curve, in systematic changes in the eclipse depths, and in emission at the Ca *H* and *K* lines in a medium-resolution spectrum we have obtained of the system. Over the course of the *TESS* observations the light and surface-brightness ratios between the stars change

linearly by 20% and 14%, respectively, but the geometric parameters do not. Studies of objects showing spot activity should account for this by using observations over long time periods where possible, and by concentrating on totally-eclipsing systems whose light-curves allow more robust measurements of the physical properties of the system.

Introduction

Detached eclipsing binaries (dEBs) are our primary source of measurements of the physical properties of normal stars[1,2] and have many astrophysical applications[1,3,4]. dEBs containing stars of similar mass to our Sun are useful in particular in helping to constrain our understanding of stellar theory in the mass regime around the solar fiducial point, for example, the amounts of internal mixing and convective core overshooting[5–7]. Solar-type dEBs can also be helpful in studying starspot configurations[8–10] and the radius discrepancy whereby low-mass stars are found to be systematically larger and cooler than predicted by theoretical models[5,11,12].

In this work we determine the physical properties of the dEB ZZ Ursae Majoris based on published radial-velocity (RV) measurements and a light-curve recently obtained by the *Transiting Exoplanet Survey Satellite* (*TESS*). Basic information on ZZ UMa is given in Table I. The *B* and *V* magnitudes come from the *Tycho* star mapper[13] on the *Hipparcos* satellite[14], and are the average of 213 measurements well distributed in orbital phase; they agree well with the dedicated observations by Lacy[15]. The 2MASS *JHK* magnitudes[16] are single-epoch and were obtained at orbital phase 0·223.

ZZ UMa was discovered to be a dEB by Kippenhahn[17,18]. Photometry and light-curve solutions have been reported by several authors[18–23]. Lacy[15,24] measured its *V* magnitude, *B–V* and *U–B* colour indices, and photometric indices in the *uvbyβ* system.

Popper[27] reported obtaining 13 high-resolution spectra which showed double lines, as part of a survey of 76 late-type dEBs. He presented a short discussion and preliminary properties, but no RVs or detailed analysis. Popper[28] gave minimum masses of $M_1 \sin^3 i = 1{\cdot}18\ M_\odot$ and $M_2 \sin^3 i = 0{\cdot}96\ M_\odot$, where i is the orbital inclination, but again no RVs were presented in his short summary paper.

TABLE I

Basic information on ZZ UMa.

Property	*Value*	*Reference*
Hipparcos designation	HIP 51411	14
Tycho designation	TYC 4144-400-1	13
Gaia EDR3 designation	1049087857023628672	25
Gaia EDR3 parallax	5·5494 ± 0·0140 mas	25
TESS Input Catalog designation	TIC 138505004	26
B magnitude	10·43 ± 0·03	13
V magnitude	9·83 ± 0·02	13
J magnitude	8·713 ± 0·029	16
H magnitude	8·412 ± 0·021	16
K_s magnitude	8·334 ± 0·014	16
Spectral type	G0 V + G8 V	22

Lacy & Sabby[29] obtained and measured RVs from 27 high-resolution échelle spectra of ZZ UMa. They combined these with the photometric results from Clement *et al.*[23] to obtain the first determination of the masses and radii of the component stars. Imbert[30] presented a spectroscopic orbit of ZZ UMa based on 49 spectra from the *Coravel* and *Élodie* instruments. The resulting masses and radii are in reasonable agreement with those from Lacy & Sabby.

In this work we revisit ZZ UMa to determine its physical properties to high precision. We base our analysis on the RVs from Lacy & Sabby[29] and Imbert[30], and on light-curves from *TESS*. A detailed scientific motivation is presented in Paper 1 of this series[31] and a review of the use of space-based photometry for the study of binary systems is given in ref. 4.

Observational material

A surfeit of photometry exists for ZZ UMa from the NASA *TESS* satellite[32], which observed it in short cadence (120-s sampling rate) in sectors 14 (2019/07/18 to 2019/08/15), 21 (2020/01/21 to 2020/02/18), 41 (2021/07/23 to 2021/08/20), and 47–48 (2021/12/03 to 2022/02/26). The light-curves show deep total and annular eclipses plus a smaller-amplitude and longer-time-scale variation which changes between and during sectors and can be attributed to starspots.

We downloaded the data for all five sectors from the MAST archive* and converted the fluxes to relative magnitude. We retained observations with a QUALITY flag of zero, yielding a total of 84 764 data points. We found the simple aperture photometry (SAP) and pre-search data conditioning SAP (PD-CSAP) data[33] to be visually almost indistinguishable, so adopted the SAP data as usual in this series of papers. The light-curves are shown in Fig. 1.

Light-curve analysis

The light-curve shows total eclipses plus a slower variation of lower amplitude due to starspots. Evolution of the starspot pattern is clear both between and during sectors. A detailed analysis of the spot properties of ZZ UMa is not the aim of the current work; we instead view it as a nuisance signal to be removed†. To this end we located every fully-observed eclipse within the *TESS* light-curve and extracted all data within one eclipse duration of the eclipse centre. A straight line was fitted to the data outside eclipse and subtracted from the light-curve to normalize it to zero differential magnitude. The result of this was a new dataset containing 26 682 data points (31·5% of the original number).

We then fitted this eclipse light-curve using version 42 of the JKTEBOP‡ code[36,37]. We fitted for the orbital period (P) and time of mid-eclipse (T_0), the sum ($r_A + r_B$) and ratio ($k = r_B/r_A$) of the fractional radii, the orbital inclination (i), and the central-surface-brightness ratio of the two stars (J). We adopted a quadratic limb-darkening (LD) law, fitted for the linear coefficients for each star (u_A and u_B) and fixed the quadratic coefficients (v_A and v_B) to theoretical values from Claret[38]. A circular orbit was adopted as we found the orbital eccentricity to be extremely small and consistent with zero. Third light was found to be

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

† A model of the starspots and their evolution could be obtained using computer codes such as MACULA (Kipping[34]) or SOAP-T (Oshagh *et al.*[35]).

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

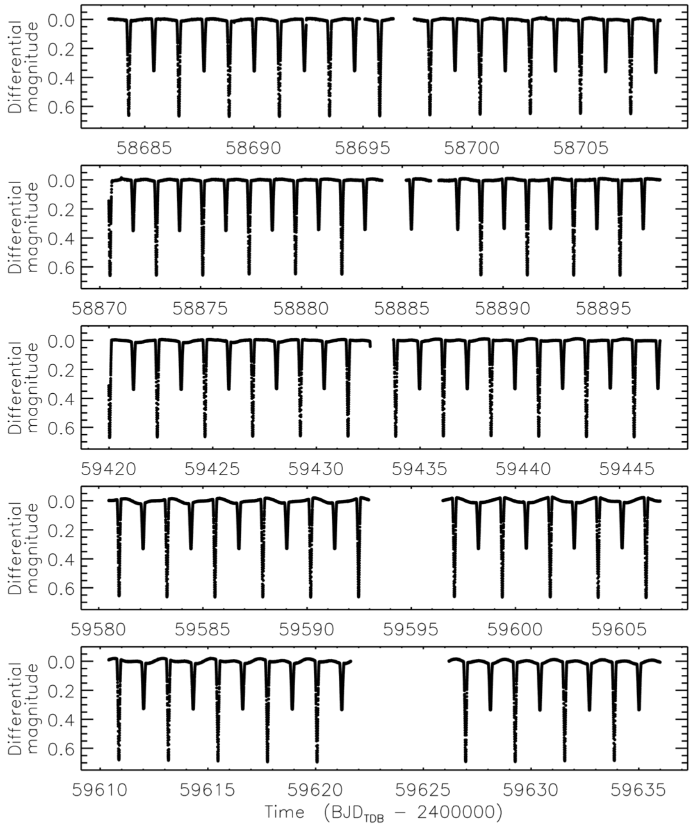

FIG. 1

TESS short-cadence SAP photometry of ZZ UMa from the five sectors. The flux measurements have been converted to magnitude units then rectified to zero magnitude by the subtraction of low-order polynomials.

insignificant and typically slightly below zero, so was fixed at zero. We term the star eclipsed at the deeper eclipse star A and its companion star B; star A is hotter, larger and more massive than star B.

The best fit is shown in Fig. 2 and has a large scatter during the eclipses. We attribute this to spots on the stellar surfaces which affect the surface-brightness ratio of the system. The increased scatter during both eclipses is evidence that both components have starspots. A closer inspection of the residuals of the fit shows that their form changes between sectors (Fig. 3) due to evolution of the starspots.

From this we decided that separate fits to subsets of the *TESS* data are necessary. We therefore modelled the data from each sector individually with the same approach as above, except that P was fixed at the value found from the fit to all data near eclipse. The residuals of these fits are shown in Fig. 4, which has been constructed in the same way as Fig. 3 so the two figures may be easily

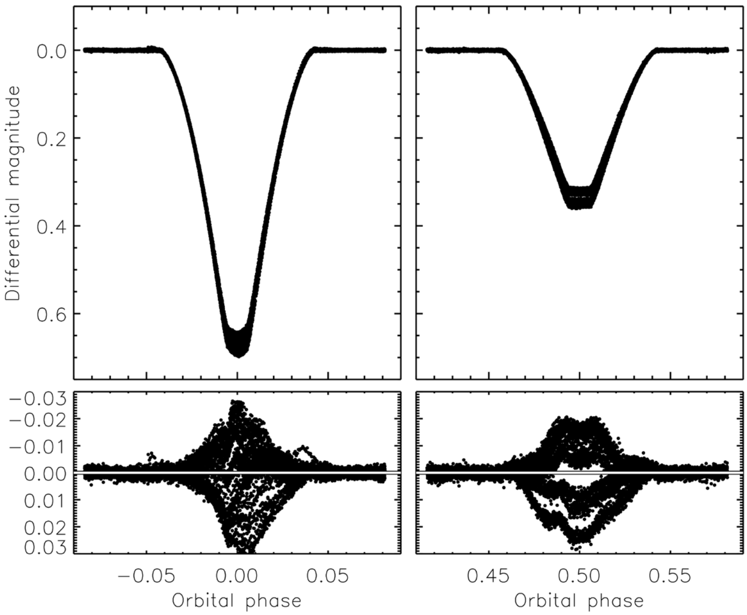

FIG. 2

Best fit to the full *TESS* light-curve of ZZ UMa using JKTEBOP for the primary eclipse (left panels) and the secondary eclipse (right panels). The residuals are shown on an enlarged scale in the lower panels.

compared. It is obvious that these individual fits give much lower residuals. This can be quantified by the scatter of the data points *versus* the best fit(s), which is 6·5 mmag for the overall fit and between 1·8 and 2·5 mmag for the individual fits. Nevertheless, some structure remains in the residuals in Fig. 4 because the effects of starspots have not been completely removed.

The expectation from the fits to the data from the individual *TESS* sectors was that the fractional radii would be reasonably consistent, as they are well determined by the contact points during the eclipses[39,40], but that the radiative parameters ($\mathcal{J}$, u_A, u_B) would change significantly with time. Such assertions require the availability of error bars, so we ran 1000 Monte Carlo simulations[36,41] to measure the 1σ uncertainties in the fitted parameters. We also experimented with further subdividing the data from each sector into two light-curves, before and after the mid-sector pause for *TESS* to downlink data to Earth. The latter results are more informative so were adopted for the following analysis.

The results of this process are shown in Fig. 5, from which three conclusions can be reached. First, there is a clear trend of decreasing surface brightness and light ratio with time indicative of variation in the radiative parameters of one or both stars. Its time-scale is a few years or more, but the current data are insufficient to infer this with any precision. Second, the wavelength-independent parameters ($r_A + r_B$, k, i) show no clear trend except for a possible variation in k and i for sectors 47 and 48. This agrees with prior expectations. Third, the error bars are much smaller than the scatter of the values of individual parameters. This was also expected because they do not allow for the changing radiative parameters of the stars.

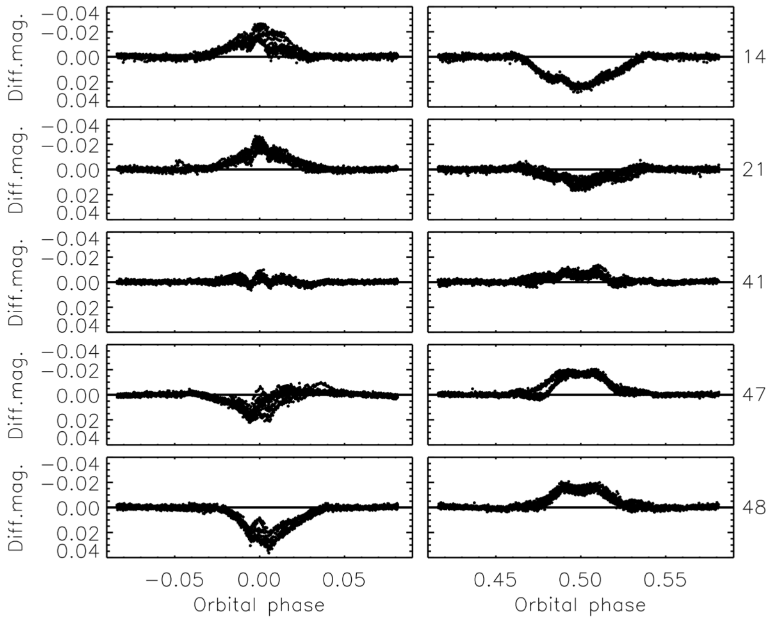

Fig. 3

Residuals of the best fit shown in Fig. 2, but separated according to *TESS* sector. The sector numbers are annotated on the right.

In the absence of an extensive study of the spot-evolution properties of the system, we consider it reasonable to adopt the mean and standard deviation of the parameter values as the final values and error bars. We use the standard deviation rather than the standard error to avoid underestimation of the uncertainties caused by the changing properties of the system. The adopted properties are given in Table II. The good news is that r_A and r_B, the most important parameters here, are measured to 0·4% precision. For completeness,

Table II

Adopted parameters of ZZ UMa measured from the TESS light-curves using the JKTEBOP *code. They represent the mean and standard deviation of the values found from fitting the ten half-sector eclipse light-curves individually.*

Parameter	*Value*
Orbital inclination (°)	89·41 ± 0·22
Sum of the fractional radii	0·26756 ± 0·00085
Ratio of the radii	0·7484 ± 0·0040
Central-surface-brightness ratio	0·552 ± 0·046
Third light	0·0 (fixed)
Linear LD coefficient for star A	0·328 ± 0·049
Linear LD coefficient for star B	−0·031 ± 0·088
Quadratic LD coefficient for star A	0·30 (fixed)
Quadratic LD coefficient for star B	0·23 (fixed)
Fractional radius of star A	0·15304 ± 0·00067
Fractional radius of star B	0·11453 ± 0·00043
Light ratio ℓ_B/ℓ_A	0·357 ± 0·020

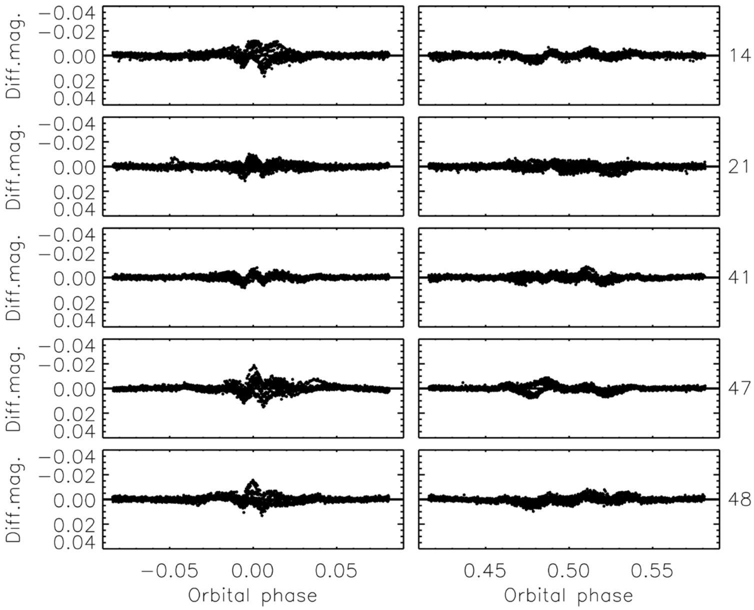

FIG. 4

Residuals of the best fits to individual *TESS* sectors, on the same scale as Fig. 3. The sector numbers are shown on the right.

the analysis based on the five light-curves from individual sectors returned results in good agreement but with slightly smaller error bars.

Orbital ephemeris

One drawback of modelling the *TESS* light-curve in multiple short segments is that a precise orbital period does not result. We therefore sought to obtain a precise orbital ephemeris based on data covering a much longer time span. We made no attempt to be exhaustive, as we note that no change in orbital period is apparent in the many timings collected on the TIming DAtabase at Krakow (TIDAK*) for ZZ UMa† (see ref. 42). The specific aim was to have an orbital ephemeris that is reliable over the time interval covering the recent *TESS* observations and the earlier spectroscopic studies in the mid-1990s that will be used below.

We began with the times of primary eclipse obtained from the ten half-sector eclipse light-curves. The error bars from the Monte Carlo analysis were significantly too small so we multiplied them by a factor of 20 to account better for their scatter *versus* a fitted linear ephemeris. To these we added published times of primary minimum obtained using CCDs or photoelectric photometers, plus the zero-point of the orbital ephemeris given by Mallama[43]. These values

* https://www.as.up.krakow.pl/ephem/

† https://www.as.up.krakow.pl/minicalc/UMAZZ.HTM

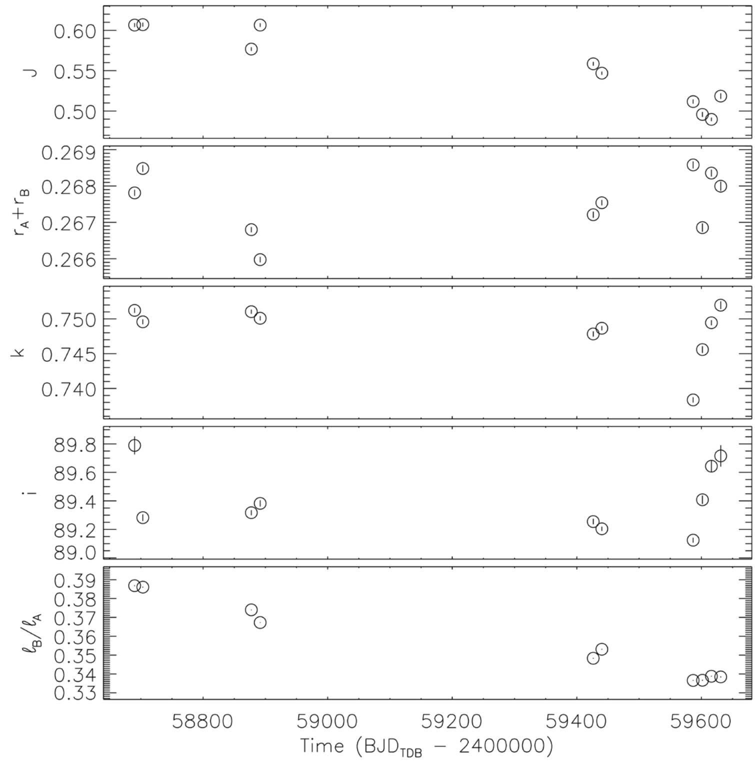

FIG. 5

Values of important parameters measured from the eclipse light-curves of each half-sector (open circles). The error bars come from 1000 Monte Carlo simulations in each case and are all smaller than the point sizes. The points are plotted *versus* the mean value of the time-stamps on the *x*-axis.

were in all cases quoted in HJD, so we converted them to BJD. When a time system was given it was always UTC, so we assumed that all published timings were on the UTC system and converted them to TDB to match those from *TESS*, using routines from Eastman *et al.*[44].

The resulting orbital ephemeris is

$$\text{Min I} = \text{BJD}_{\text{TDB}}\ 2454945{\cdot}669574(49) + 2{\cdot}299260291(39)E, \qquad (1)$$

where E is the cycle number since the reference time and the bracketed quantities indicate the uncertainties in the last digits of the preceding number. The reduced χ^2 of the fitted ephemeris is $\chi^2_\nu = 1{\cdot}75$ so the error bars in the ephemeris above have been multiplied by $\sqrt{\chi^2_\nu}$ to account for this. This excess scatter in the eclipse timings beyond the quoted error bars can be attributed to the spot activity shown by ZZ UMa. The times of minimum used in this analysis are given in Table III and the residuals of the fit are shown in Fig. 6.

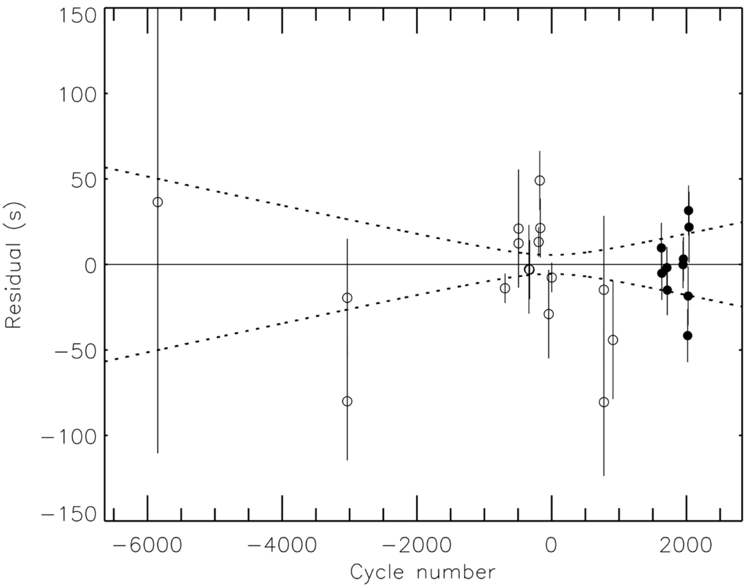

Fig. 6

Observed-minus-calculated (O–C) diagram of the times of primary minimum *versus* the fitted linear ephemeris. Timings from the *TESS* data are shown with filled circles. Timings from the literature are shown with open circles. The dotted lines indicate the 1σ uncertainty in the ephemeris determined from these data.

Radial velocities

Two sets of high-quality spectroscopic orbits for both components of ZZ UMa are available. Lacy & Sabby[29] obtained 27 high-resolution spectra and measured RVs for both components in each. Imbert[30] presented 33 RVs for star A, of which 28 were from *Coravel*[56] and five from *Élodie*[57], and 16 RVs for star B, of which 12 were from *Coravel* and four from *Élodie*. The *Coravel* RVs have a greater scatter than those from Lacy & Sabby, whereas the *Élodie* RVs have a much lower scatter.

We reanalysed both sets of RVs independently in order to ensure that the published velocity amplitudes, K_A and K_B, and uncertainties were reliable. In each case we modelled the RVs of both stars together but fitted for the individual systemic velocities, $V_{\gamma,A}$ and $V_{\gamma,B}$. A circular orbit was assumed and the ephemeris was fixed at that found in the previous section. Informed by our work[58] on V505 Per we used 1000 Monte Carlo simulations to determine the error bars for the fitted parameters.

The results for the Lacy & Sabby[29] RVs are shown in Fig. 7. No data errors were given for the RVs so we weighted them equally for each star. Our results are in good agreement with those from Lacy & Sabby[29], and our error bars are slightly smaller.

The fitted orbits for the Imbert[30] RVs are shown in Fig. 8. We found that the uncertainties quoted for the *Élodie* RVs for star A were significantly smaller

TABLE III

Times of published mid-eclipse for ZZ UMa and their residuals versus the fitted ephemeris.

Orbital cycle	*Eclipse time* (BJD_{TDB})	*Uncertainty* (*d*)	*Residual* (*d*)	*Reference*
−5848·0	2441499·59581	0·00170	+0·00042	43
−3035·0	2447967·41436	0·00040	−0·00023	45
−3035·0	2447967·41366	0·00040	−0·00093	45
−693·0	2453352·28203	0·00010	−0·00016	46
−492·0	2453814·43365	0·00010	+0·00014	47
−492·0	2453814·43375	0·00040	+0·00024	48
−338·0	2454168·51956	0·00030	−0·00003	49
−328·0	2454191·51216	0·00020	−0·00004	49
−177·0	2454538·70107	0·00020	+0·00057	50
−170·0	2454554·79557	0·00020	+0·00025	50
−194·0	2454499·61323	0·00010	+0·00015	51
−44·0	2454844·50178	0·00030	−0·00034	52
0·0	2454945·66949	0·00010	−0·00009	53
774·0	2456725·29687	0·00050	−0·00017	54
775·0	2456727·59537	0·00050	−0·00093	54
909·0	2457035·69667	0·00040	−0·00051	55
1628·0	2458688·86544	0·00017	+0·00011	*TESS* (this work)
1634·0	2458702·66083	0·00018	−0·00006	*TESS* (this work)
1710·0	2458877·40465	0·00014	−0·00002	*TESS* (this work)
1716·0	2458891·20006	0·00017	−0·00017	*TESS* (this work)
1949·0	2459426·92788	0·00016	−0·00000	*TESS* (this work)
1955·0	2459440·72348	0·00015	+0·00004	*TESS* (this work)
2018·0	2459585·57636	0·00018	−0·00048	*TESS* (this work)
2025·0	2459601·67145	0·00020	−0·00021	*TESS* (this work)
2031·0	2459615·46759	0·00017	+0·00036	*TESS* (this work)
2038·0	2459631·56230	0·00024	+0·00025	*TESS* (this work)

than the scatter of the RVs themselves so we doubled them for both stars. The RV uncertainties for each star were subsequently scaled to give $\chi^2_\nu = 1{\cdot}0$. We found a slight disagreement in K_B for the Imbert RVs. Investigating this showed that the K_B is sensitive to the T_0 value used. We therefore recalculated all the orbits with T_0 fitted but P fixed. This effect may be due to an inaccurate orbital ephemeris or to errors in the time-stamps provided with the Imbert RVs. As the same problem was not found for the Lacy RVs, we suspect the latter.

Table IV presents the parameters of the spectroscopic orbits from the literature and those found here. There is excellent consistency between different results. To obtain the final K_A and K_B we calculated the weighted mean of the individual values. The choice of whether to fix or fit T_0 has an effect on the final K_A and K_B values smaller than their uncertainties.

Chromospheric emission

Magnetic fields in low-mass stars cause starspots[59,60] and chromospheric emission in lines such as Ca II *H* and *K*[61–63]. ZZ UMa shows evidence for the former phenomenon, and we had an opportunity to observe the latter. We obtained a single spectrum of ZZ UMa on the night of 2022/06/08 using the *Intermediate Dispersion Spectrograph* (*IDS*) at the Cassegrain focus of the *Isaac Newton Telescope* (*INT*). Thin cloud was present, which decreased the count rate of the observations. We used the 235-mm camera, H2400B grating, EEV10 CCD, and a 1-arcsec slit in order to obtain a resolution of approximately 0·5 Å, the highest currently available with this spectrograph. A central wavelength setting of 4050 Å yielded a spectrum covering 373–438 nm at a

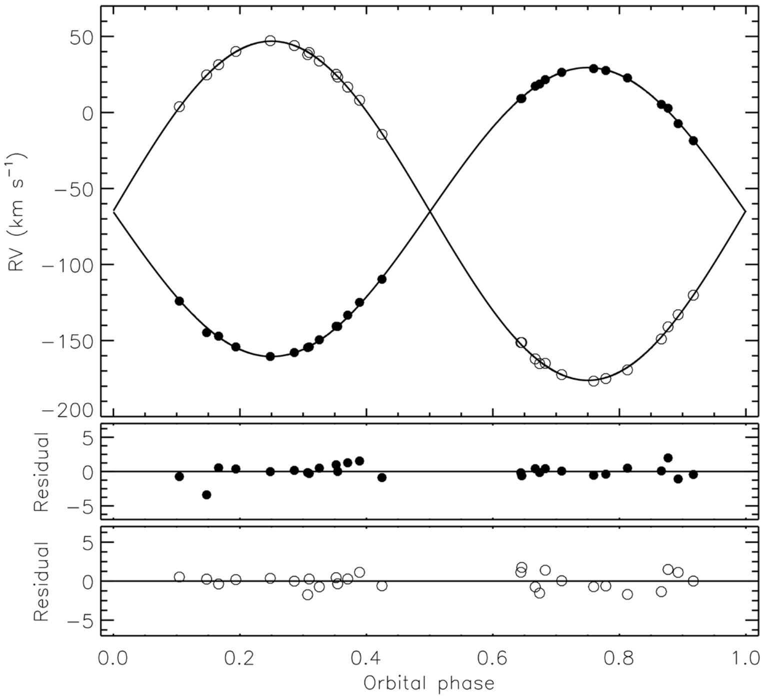

FIG. 7

RVs of ZZ UMa measured by Lacy & Sabby[29] (filled circles for star A and open circles for star B) compared to the best-fitting spectroscopic orbits from JKTEBOP (solid curves). The residuals are given in the lower panels separately for the two components.

reciprocal dispersion of 0·023 nm px^{-1}. The data were reduced using a pipeline currently being written by the author, 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.

TABLE IV

Spectroscopic orbits for ZZ UMa from the literature and from the reanalysis of the RVs in the current work. All quantities are in km s^{-1}.

Source	K_A	K_B	V_γ	$V_{\gamma,A}$	$V_{\gamma,B}$	*rms residual*
Lacy & Sabby[29]	95·1 ±0·3	111·8 ±0·3		−65·7 ±0·2	−64·8 ±0·2	
This work	95·01 ±0·23	111·52 ±0·24		−65·50 ±0·18	−64·65 ±0·18	0·96, 0·96
Imbert[30]	94·99 ±0·33	112·03 ±0·39	−65·22 ±0·20			1·73, 1·96
This work	94·89 ±0·18	111·75 ±0·27		−64·86 ±0·14	−65·36 ±0·23	2·00, 2·05
Final values	94·94 ±0·18	111·62 ±0·40				

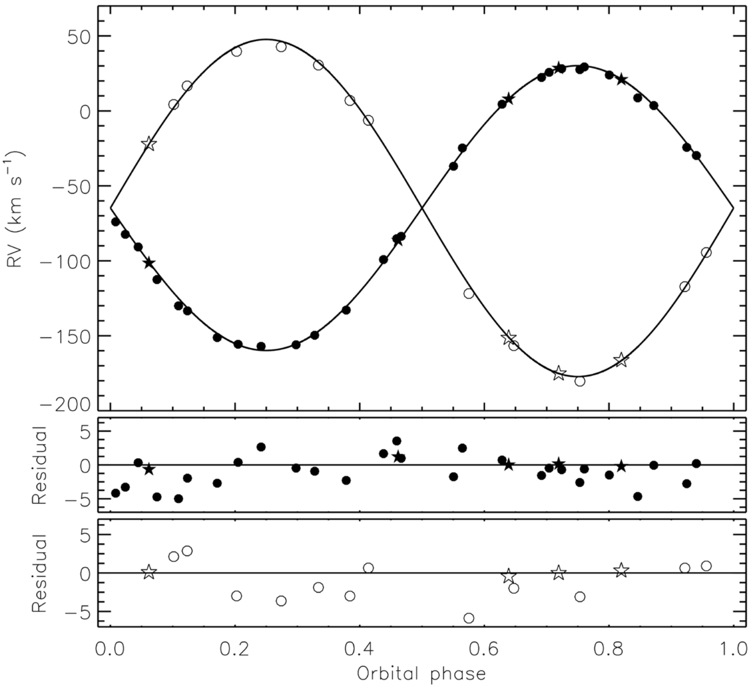

FIG. 8

RVs of ZZ UMa measured by Imbert[30] (filled symbols for star A and open symbols for star B) compared to the best-fitting spectroscopic orbits from JKTEBOP (solid curves). The residuals are given in the lower panels separately for the two components. The circles show RVs from *Coravel* and the stars show RVs from *Élodie*. The axis ranges are the same as those in Fig. 7 so they may be compared easily.

Fig. 9 shows the resulting spectrum in the region of the *H* and *K* lines compared to an analogous synthetic spectrum from the BT-Settl model atmospheres[64,65]. Emission in the cores of the calcium lines is obvious and confirms that the system shows chromospheric activity. The spectrum was taken at orbital phase 0·9037 where the RV difference between the stars was 117 km s^{-1} (approximately 3·5 pixels). The emission lines from the two stars overlap so it is not possible to assess the emission strengths from the two stars individually.

Physical properties of ZZ UMa

The physical properties of the system were calculated using the r_A, r_B, and i from Table II, the orbital period determined above, and the final K_A and K_B values from Table IV. We used standard formulae[66] and the reference solar values from the IAU[67], as implemented in the JKTABSDIM code[68]. The results are given in Table V and show good news: the masses are measured to precisions of 0·8% and 0·5%, and the radii to 0·5% and 0·4%. The main limitation is the lower precision of K_B, which is in turn due to the minor disagreement between the two sources of published RVs.

A comparison with the properties measured by Lacy & Sabby[29] shows excellent agreement for the masses (as expected) but not for the radii: we find

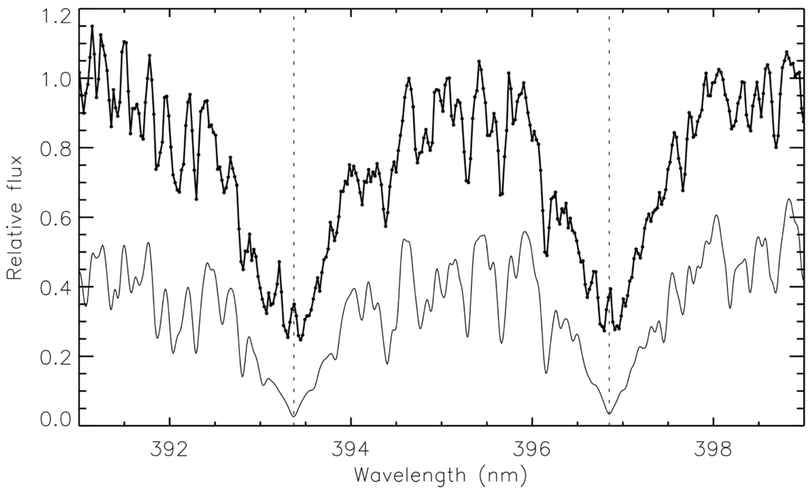

FIG. 9

Observed spectrum of ZZ UMa around the calcium *H* and *K* lines (thick upper line with points) compared to a synthetic spectrum for a star with $T_{eff} = 6000$ K, log $g = 4{\cdot}5$ and solar metallicity from the BT-Settl model atmospheres[64,65] (thin lower line). The *H*- and *K*-line central wavelengths are shown with dotted lines. The spectrum of ZZ UMa has been shifted to zero velocity and normalized to unit flux. The synthetic spectrum has been scaled so as to be clearly visible below the observed spectrum.

values significantly lower than the 1·51 ± 0·02 and 1·16 ± 0·01 $R_\odot$ given by Lacy & Sabby[29]. We expect our own radius measurements to be more reliable as they are based on light-curves of much better quality and greater quantity than in previous studies.

The effective temperatures (T_{eff}s) of the stars were determined by Lacy & Sabby[29] based on the intrinsic $(b - y)_0$ colour indices of the stars, which come from the combined colour indices, the light ratios in the *b* and *y* light-curves from Clement *et al.*[22], and the intrinsic flux calibration by Popper[69]. This approach is at first impression quite outdated, but can be checked using external

TABLE V

Physical properties of ZZ UMa defined using the nominal solar units given by IAU 2015 Resolution B3 (ref. 67).

Parameter	*Star A*	*Star B*
Mass ratio	0·8505 ± 0·0034	
Semi-major axis of relative orbit ($R^N_\odot$)	9·388 ± 0·020	
Mass ($M^N_\odot$)	1·1348 ± 0·0087	0·9652 ± 0·0051
Radius ($R^N_\odot$)	1·4367 ± 0·0070	1·0752 ± 0·0046
Surface gravity (log[cgs])	4·1782 ± 0·0041	4·3597 ± 0·0034
Density ($\rho_\odot$)	0·3826 ± 0·0051	0·7765 ± 0·0089
Synchronous rotational velocity (km s^{-1})	31·61 ± 0·15	23·66 ± 0·10
Effective temperature (K)	5960 ± 70	5270 ± 90
Luminosity log($L/L^N_\odot$)	0·370 ± 0·021	−0·095 ± 0·030
M_{bol} (mag)	3·814 ± 0·052	4·978 ± 0·075
Distance (pc)	180·8 ± 1·9	

information. First, we used the surface-flux ratio in Table II to determine an approximate $T_{\rm eff}$ ratio of 0·862 ± 0·018 which gives $T_{\rm eff,B}$ = 5138 ± 107 K for a $T_{\rm eff,A}$ of 5960 K, in acceptable agreement with the $T_{\rm eff,B}$ from Lacy & Sabby[29]. This point is only weak evidence because the variation in radiative parameters seen in the *TESS* light-curves means our measurement of the surface brightness ratio may not be representative of its average value. Second, we determined the distance to the system using the method of Southworth *et al.*[68] which relies on the surface brightness *versus* $T_{\rm eff}$ calibrations of Kervella *et al.*[70]. The *K*-band measurement gives a distance of 180·8 ± 1·9 pc assuming an interstellar extinction of $E(B-V)$=0·00 ± 0·01; a larger interstellar extinction can be ruled out by requiring the distances found in the *BVJHK* bands to be consistent. The *Gaia* EDR3 parallax[25] gives a distance of 180·20 ± 0·45 pc by simple inversion. Based on this, we accepted the $T_{\rm eff}$ values from Lacy & Sabby[29] as reliable.

Comparison with theoretical models

The precise measurement of the properties of the stars, in particular for the slightly-evolved star A, means a comparison with theoretical evolutionary models could be informative. We did this, using tabulations from the PARSEC models[71], *via* the mass–radius and mass–$T_{\rm eff}$ diagrams[72,73] (Fig. 10). We did not consider any constraints on metallicity as there are no precise determinations available.

The mass, radius, and $T_{\rm eff}$ of star A can be matched by a metallicity in the region of Z = 0·02 or slightly higher, with an age in the region of 5·5 Gyr depending on the adopted Z. Theoretical models with Z = 0·017 predict a significantly higher $T_{\rm eff}$ than observed, and models with Z = 0·030 predict the opposite. We infer that the system has an approximately solar metallicity and that star A does not contradict stellar theory.

The less-massive star B, however, causes a problem for the theoretical models. It is not possible to match its properties for any combination of age and metallicity available in the PARSEC tabulations. It is much too large and cool to match any theoretical predictions simultaneously with star A (see Fig. 10), and the closest we can get is for Z = 0·06 and an age of 8·5 Gyr, where its radius is well matched but it is still slightly too hot for the models. By comparison to its predicted properties for the same age(s) and metal abundance(s) as star A, it is 0·12 $R_\odot$ (11%) larger and 330 K (6%) cooler, but these effects cancel to give it the expected luminosity.

A *radius discrepancy* is known to exist for late-type dwarfs in the sense that they have larger radii and lower $T_{\rm eff}$s than predicted by stellar theory[5,11,12,74,75]. This has been attributed to the inhibition of convection[76,77] due to magnetic fields and/or starspots. There is evidence that stars in short-period binaries are affected in a qualitatively different way[76] because tidal effects cause them to rotate more quickly and thus show stronger activity. However, the radius discrepancy has also been found in longer-period binaries[78] and single stars[5,12], and there are also examples of stars in short-period binaries that do *not* show the discrepancy[79–81]. Recent analyses have found a large scatter in the size of the radius discrepancy between and even within binary systems[82,83]. Under the assumption that the age and metallicity of the ZZ UMa system can be inferred from the properties of star A, the poor agreement between theoretical models and the measured properties of star B make it an excellent candidate for a star showing the radius discrepancy. ZZ UMa B is another example of a star in the region of 1 $M_\odot$ showing the radius discrepancy.

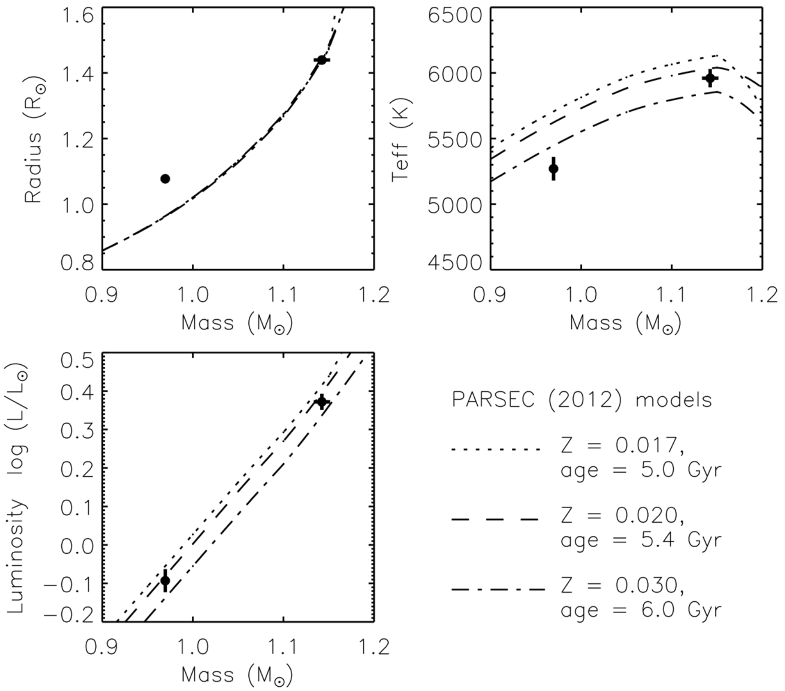

FIG. 10

Comparison between theoretical predictions from the PARSEC models[71] and the measured physical properties of ZZ UMa for mass *versus* radius, T_{eff}, and luminosity. The ages and metal abundances of the chosen theoretical predictions are given in the key on the lower right.

An updated version of the PARSEC model grid, denoted 1·2S, has been computed[84] with a revised temperature *vs.* optical-depth prescription based on sophisticated model atmospheres of low-mass stars[64,65]. These provide a better match to the observed properties of low-mass stars. However, they are not useful in the current situation as the modifications cover only masses of 0·7 $M_{\odot}$ and lower.

Summary and conclusions

ZZ UMa is a solar-type dEB which shows total eclipses with an orbital period of 2·299 d and evolving starspot activity. We have determined its physical properties based on two high-quality sets of RVs available from the literature and light-curves from five sectors of observations with the *TESS* satellite. The two RV datasets agree with each other very well for the primary star but not quite so well for the secondary star, but do allow mass determinations to 0·8% and 0·6%, respectively.

The light-curve of ZZ UMa varies during and between *TESS* sectors due to starspot evolution, which manifests itself as a slow variation with time (as spots rotate in and out of view), emission in the calcium *H* and *K* lines, and changes in the depths of the eclipses. By modelling each *TESS* half-sector separately, we have found slow variations in the light and surface-brightness ratios between the stars indicative of spot-induced changes in their radiative properties. The geometric parameters (r_A, r_B, and i) show much smaller changes because they are derived primarily from the contact points during the total and annular eclipses. We were therefore able to measure the radii of the stars to 0·5% precision. Unfortunately, no further observations with *TESS* are scheduled for this system. It would be interesting to identify a similar dEB in either the *TESS* continuous viewing zones or that has been observed using the *Kepler* satellite, for which the spot evolution could be tracked in the same way over a longer and/or better-sampled time period.

The properties of star A match predictions from the PARSEC models for an age of approximately 5·5 Gyr and a slightly super-solar metal abundance around $Z = 0{\cdot}02$. Star B does not match these or any other predictions, having too large a radius and too low a $T_{\rm eff}$ to agree with the theoretical models. Its luminosity is consistent with the models because the radius and $T_{\rm eff}$ offsets cancel. Star B therefore is an excellent example of the *radius discrepancy* well known to affect low-mass eclipsing binaries, and at 0·97 $M_\odot$ is one of the most massive stars to show this effect clearly.

An alternative interpretation is that ZZ UMa is younger than we infer from matching star A to the predictions of theoretical models, and that *both* stars show the radius discrepancy. This could be investigated using dEBs with external constraints on their ages (and chemical compositions), *e.g., via* membership of an open cluster[85–87].

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CORRESPONDENCE

To the Editors of 'The Observatory'

Comments on Recent Issues

The 2022 June issue of *The Observatory* contains several items of personal interest to me. For example, I remember when the old house at 49 Bay State Road (mentioned by Virginia Trimble on p. 125) was part of the group of houses to which *Sky & Telescope* moved when they were crowded out of old Building B that housed the Harvard Plate Stacks (mentioned by Dava Sobel on p. 86).

I was a bit surprised that Jay Pasachoff hadn't known about Harlow Shapley's interest in ants (p. 118 of the June issue). I first learned of it about 1953 or '54, when Shapley came to my college to give a set of lectures. Of course there were a couple of afternoon talks on astronomy in the Physics Department; Oberlin had no astronomers, and its one astronomy course was so low-level that it was not open to juniors or seniors majoring in a physical science. But his posted schedule also included an evening lecture in the Zoology Department, entitled 'Formicine Episodes'. (The title baffled most of my fellow students.) In it, Shapley told of his adventures searching for ants, including the incident in the Kremlin that's on p. 118. A few years later, I managed to see him sitting at his round table, just before he cleared out his office. And again I heard the story of the Russian ant; so he certainly didn't conceal this interest.

William Tyler Olcott, the former owner of some of the books Virginia Trimble found interesting, was not only a co-founder of the AAVSO, but was inspired by a public lecture by E. C. Pickering to write *A Field Book of the Stars*, which in turn encouraged my own interest in astronomy around 1945. Pickering himself was mentioned on pp. 85–86 of the June issue, and his portrait used to hang in the corridors of the old HCO building.

Virginia Trimble's review of Abbot's book on *The Sun* touches on several related items on which I can cast some light. She wonders who 'Schmidt' and 'W. H. Julius' were; they are mentioned several times in the annotated bibliography of atmospheric refraction at

https://aty.sdsu.edu/bibliog/bibintro.html
and
https://aty.sdsu.edu/bibliog/bibliog.html

In brief: Julius was a student of Buys Ballot's, and in turn was Marcel Minnaert's thesis advisor (for Minnaert's *second* Ph.D.; his first was in photobiology, which was how he got interested in sunlight). The 'Schmidt' mentioned by Abbot would be August Schmidt. Both Schmidt and Julius had nutty theories about the solar atmosphere and sunspots. However, their crank theories were different; each regarded the other as misguided at best. They both thought refraction in the solar atmosphere was important. Schmidt wanted normal refraction to explain sunspots and the sharp-edged photosphere; Julius had a whole set of crank explanations of solar (and other) phenomena based on anomalous dispersion. Both are quite properly forgotten today, though it took decades for their theories to vanish, long after their errors were pointed out. The *ApJ* published Albert Einstein's obituary of Julius in 1926; according to Einstein, it was Schmidt's paper that got the physicist Julius interested in solar physics. Einstein had some good words for their crackpot theories, even at that late date; so it's hardly surprising that Abbot mentioned them in 1911, though they really had been well refuted earlier in the century.

According to Kleinschmidt's 1929 obituary of him, Schmidt was really Carl August von Schmidt. He was more favourably regarded by the geophysics community, and was primarily remembered for his work in seismology, though he also served as head of the Stuttgart weather office. This whole group is tied together by Minnaert's 1973 biography of Julius in the *DSB*. But even he seems to have shared their misunderstanding of the difference between radiance and irradiance, which was the basic error behind it all. If you want to find all the gory details, they are in the bibliography mentioned above.

I myself was familiar with Abbot's work on the Sun from writing a short 'research' paper for a freshman English class as an undergraduate, years before I ever took a course in astronomy. So when I arrived at Harvard in 1955, I was shocked to learn that the Smithsonian Astrophysical Observatory was being transferred from Washington, D.C., to Cambridge, Mass. — and that Fred Whipple (who was taking over the position formerly held by Abbot) was starting it off there by refuting all of Abbot's work. Of course, I eventually learned that Abbot had no understanding of statistics, and had spent his career analyzing errors in the observations.

Finally, a few words about T. J. J. See. Virginia Trimble finds it remarkable that "Abbot found one paper by the infamous" See worth citing. But if one looks into the facts of See's career, it is not so remarkable. The academic records at the University of Missouri confirm that he was, indeed, the most brilliant student ever to pass through the University. He made a great impression on William Larkin Webb (1857–1931), an amateur astronomer, editor of a newspaper named *Progress* in Independence, Missouri, and a member of the General Assembly, and author of books on Missouri history.

See went on to do graduate work in Berlin, and published a compendium of the orbits of visual binaries which was well received by the astronomical establishment. His subsequent work was summarized in a paper in *JHA* by Thomas J. Sherrill in 1999 which is fairly complete, but omits the origin of the infamous *Brief Biography* of See published by Webb in 1913. This was written by Webb to support See's campaign to become the director of the Naval Observatory, which was entangled in political controversy that is recorded in the Congressional Record. According to correspondence between See and Webb that is preserved in the See papers at the Library of Congress, Webb's original idea was to produce a single volume advancing the careers of two of his Missouri heroes: the astronomer See, and the politician Champ Clark; the proposed title was to be *The Statesman and the Scientist*. Apparently this proved to be too unwieldy an undertaking, and in the end there were two books: *Champ Clark*, and *A Brief Biography and Popular Account of the Unparalleled Discoveries of T. J. J. See*.

Both books are written in the same hero-worshipping style. In fact, I have seen the original handwritten family history that See compiled at Mare Island when he thought he was dying of appendicitis, and later supplied to Webb to be incorporated in the book. It was perfectly straightforward, with none of the bombast that has made the *Brief Biography* so ridiculed over the years. Plainly, the hyperbole of Webb's book about See was entirely Webb's own contribution. Unfortunately, See's handwritten memoir was in the possession of his niece Ada See, who would not allow it to be copied or photographed. Apparently, a large part of See's later overconfidence in his own ideas was due to believing his own publicity agent, W. L. Webb.

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2022 June 6

REVIEWS

The Sun and Other Stars of Dante Alighieri: A Cosmographic Journey through the Divina Commedia, by Sperello Alighieri & Massimo Capaccioli (World Scientific), 2022. Pp. 170, 23·5 × 16 cm. Price £50 (hardbound; ISBN 978 981 124 549 7).

The year 2022 has been, it seems, to have been a good one for Dante, with both this book and an evening-long ballet score by Thomas Adès performed on April 28 by the Los Angeles Philharmonic under Gustavo Dudamel. Does Dante Alighieri (1265–1321) count as an astronomer? Well, he appears in the second edition of the *Biographical Encyclopedia of Astronomers* (pp. 505–507) in an article by Dennis Danielson of the University of British Columbia, who also included a Dante extract in his 2000 *The Book of the Cosmos* (pp. 89–91). Danielson's medieval cosmology sage is C. S. Lewis, and the translation quoted dates from about 1895 and was the work of Henry Wadsworth Longfellow.

In between, as it were, Dorothy L. Sayers (yes, the 'literary agent' of Lord Peter Wimsey and Harriet Vane) provided a short section on 'Dante's Universe' in her version of *Hell* (*Inferno*), published by Penguin in London in 1949. And the eventual translation of volume three, *Paradise* (1962), has a couple of pages on 'Astronomy in Paradise' (pp. 350–351).

The present authors ask the broader question: Was Dante a scientist? Or, rather, "Can we say that Dante was a scientist?" Their answer comes in the form of a quick overview of what previous writings Dante would have had access to (Thomas Aquinas, Albertus Magnus, Augustine of Hippo, Orosius, Peter Lombard, and above all Aristotle). After quoting a brief Paul Dirac *versus* Robert Oppenheimer encounter, they conclude that "Alighieri's poetry is the harmonius garment for a scientific treatise with no equal, the sum of knowledge and fruitful intuitions."

Where did the name come from? Chapter 3 tells us that Dante is a shortened version of Durante, and that the father's name was Alighieto of Bellincione of Alighiero. The near duplication of first and last reminds us of Galileo Galilei a few centuries later (1564–1642).

What all can we easily take away from the *Cosmographic Journey*? First an abbreviated history of Europe, especially Italy, from 476 to 1313 CE. Second, an even more abbreviated description of the evolution of (mostly) Greek astronomy from Thales (*c.* 585 BCE) to Ptolemy (*c.* 100–175 CE). These chapters include brief Dante excerpts, indicating he was aware of both the histories.

Third are some items more specific to Dante and the *Divina Commedia*. Di Serego Alighieri (yes, he is a descendant) and Capaccioli deduce that the journey down into Hell and the centre of the Earth began with the meeting with Virgil on 1301 March 25; that they reached the centre on the evening of March 26 (Palm Sunday that year), quickly reversed direction climbing back up from Hell to reach the top of Purgatory at noon on the 30th; and that finally they took a day and a half to climb up through the heavens, reaching the Empyrean at midnight on Good Friday, March 31st, for a total of less than a week out of Dante's imaginary life and Virgil's posthumous one.

The authors point out that Dante was aware of how the Julian calendar had drifted out of step with the Sun (by about ¾ of a day each century), so that Easter wasn't actually falling on Easter. And Dante is able to figure out the date of the creation after encountering Adam in Canto XXVI of *Paradiso*. It was 5197 BCE (plus or minus a year zero). Other estimates for comparison are the 4004 BCE of Archbishop Ussher, and since the year 5782 on the Jewish calendar began on 2021 September 7, the counting must have started around 3761 BCE. Byzantine and Chinese calendars yield rather similar numbers. We conclude that if you attempt to determine the age of the Earth from written documents, you will get something like the age of human writing.

We come at last to the heart of *The Sun and the Other Stars* (that exact phrase appears in one of the translations, but I've lost it). This heart is the quotation, in the original early 14th Century Italian, of 100 passages from the *Divine Comedy* (23 from *Inferno*, 42 from *Purgatorio*, and 34 from *Paradiso*), plus the authors' translations and explanations and contextualizations. The whole work also has exactly 100 Cantos (but the extracts are not one each). Of course there are micro-glitches: page 79 speaks of secular years where century years are meant, and one is given to believe that Polaris was already a good North Star before 1300 CE, and that the relative brightnesses of the brightest stars have changed sensibly in a millennium or two. For most of the quoted passages, one's reaction is that, if I had been there, then, indeed I would have seen what Dante describes and thought what he is thinking about it, though of course I could not possibly have described it so beautifully, in any language. Bad luck intervened, and I started with the first passage in the Moon chapter. *Purgatorio* Canto X lines 12–16, which says "*E questo fece i nostri passi scarsi, tanto che pria lo scemo de la luna rigiunse al letto suo per ricorcarsi, che noi fossimo fuor di quell a cruna*;" which the authors translate as "And this made our steps so slow that the hollow of the Moon reached its bed to lie down before we came forth from that needle's eye." (*Purgatorio* X. 12–16).

The authors provide the further explanation: "In fact since three days had passed from the full moon, the dark edge was facing west, in accordance with the rule of thumb 'hump to the east waning moon, hump to the west crescent moon, where the "hump" is the luminous edge." (In Italian it rhymes, *gobba levante luna calante gobba a ponente luna crescente*.) Even with the additional essential information that, by "crescent", they mean just the waxing crescent, I couldn't quite sort this out. I turned to a scientific historian colleague whose Italian is his second language (my theory was anyone who was schooled in Italy with it as first language would have studied Dante and know what it was supposed to mean). Said historian provided both an own translation and a 'looked up' one as follows:

"And this is what our recent steps achieved, While the fool in the moon was praying, And went back to his bed to relax himself;" and, "And this our footsteps so infrequent made, That sooner had the moon's decreasing disk, Regained its bed to sink again to rest." Are these three the same or different? I'm not sure (or as another confused writer said, "I've got to go away and figure this out"). Many of the other passages, in the Moon chapter where I started and others, seem to be clear examples of what an educated early 14th Century Italian could reasonably have known or thought. Perhaps just bad luck on the starting point, and I would be very interested to hear what other readers of *The Observatory* might make of both the translations and the book in general. — VIRGINIA TRIMBLE.

A Brief History of Timekeeping: The Science of Marking Time, from Stonehenge to Atomic Clocks, by Chad Orzel (One World), 2022. Pp. 336, 19·5 × 13 cm. Price £15·99 (paperback; ISBN 978 0 86154 215 4).

I grew up reading popular-science books by Isaac Asimov. Since then, most such books I have read are somehow not as good.* This book probably comes the closest to those of my fond childhood memories. I've been aware of Orzel, a professor at Union College in Schenectady, New York (the book is based on a course he teaches), for a while, as he is relatively well known as an author of popular-science books, but life is short and these days I need a special reason to read a book. In this case, I was prompted by a positive review by a history-of-science blogger[1] (who doesn't hesitate to write a negative review if appropriate). At well over 300 pages of small print, it is not exactly brief, even though it concentrates on just the (history of) astronomy and physics of timekeeping rather than the sociological aspects as well, but everything is worth reading. Most of the topics will be familiar to most readers of this *Magazine*, but probably only experts on the history of timekeeping will learn nothing new.

The contents are broad: prehistorical timekeeping structures, calendars and reforms thereof, Mayan timekeeping, water clocks, mechanical clocks, celestial mechanics and timekeeping, the lunar method of longitude determination, traditional pocket- and wrist-watches, time zones and international time coordination, Special Relativity, atomic clocks, General Relativity, modern quartz timepieces, and the next step beyond current atomic clocks. Except for the two chapters on relativity, I learned something new in every chapter. In addition to the main narrative, there are sections set in a different typeface with a grey band at the inner margins (and presumably an intended one at the outer margins, which is usually barely perceptible) which explain certain

*The popular-science books by the late John Barrow are also very good, but not directly comparable, as they often contain his own insights, rather than 'just' recounting what is already known.

topics in more detail; they can be skipped or read later for those who like a more straightforward narrative. The mixture of familiar and less-familiar topics and additional information which adds to rather than distracts from the main narrative make the book particularly enjoyable to read.

I noticed just a few factual errors, none of which impact the main narrative (and definitely should not detract from my positive impression): warmer weather in summer is attributed to the longer length of the day (which certainly plays a role) but the angle of sunlight isn't mentioned with regard to that; Eratosthenes's measurements proved that the Earth is round (actually, they assume that and the fact that the Sun is far away — a nearby Sun would lead to its azimuth angle at noon, say, changing with 'latitude' even on a flat Earth); although later described more correctly, at first one gets the impression that Tycho and Kepler met by chance when the former travelled from Hven to Prague; Kepler is described as Austrian rather than German. A couple of other passages are somewhat confusing, but those and other errors (typos, style) are few, even in absolute terms despite the length of the book.

There are a few black-and-white figures scattered throughout the book. Footnotes as opposed to end notes are welcome. There is no list of references as such, but books and articles are mentioned when appropriate and the main text is followed by seven suggestions for further reading. The nine-page even-smaller-print index is comprehensive*.

It takes much more than an hour to read the book, but a one-hour talk by Orzel based on the book can be found on YouTube[2] (in colour, in contrast to the book); it shouldn't be a replacement for but rather an addition to the book. The book is very well written and a real page-turner. Anyone interested in the history of timekeeping will find something valuable here. — Phillip Helbig.

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Our Place in the Universe — II. The Scientific Approach to Discovery, by Sun Kwok (Springer), 2021. Pp. 344, 23·5 × 15·5 cm. Price £24·99 (paperback; ISBN 978 3 030 80259 2).

My overall impression is of a very carefully organized book in which clear explanations are seen as the key to understanding the process by which scientific discoveries are made. The author attempts, with as little fuss as possible, to go through the sequence of observations, experiments, and societal pressures that have led to our current understanding of the Earth's place, in space and time, in the Universe, including how such an understanding has affected this planet's human inhabitants. All of this is mostly done without resorting to the shorthand of mathematics, although a set of appendices provide some mathematical derivations for those that are interested.

The first volume of *Our Place in the Universe* was enthusiastically reviewed by Peredur Williams in these pages (**138**, 72, 2018). That edition titled, *Our Place in the Universe: Understanding Fundamental Astronomy from Ancient Discoveries*, took us from ancient times to Newton. The aim was to present the uncovering of our place in the Universe by showing — as Williams says in his glowing review — "the process of discovery, not just the outcome, and

*Sometimes too comprehensive: "Brahe, Tyge Ottesen "Tycho"" is the expected entry; there is also an entry for *Tycho Brahe* pointing to an italicized (for emphasis) occurrence of his name in the text.

this is achieved through clear exposition and consideration of alternatives."

Volume 2, *The Scientific Approach to Discovery*, is a follow-up that treads a similar idealistic path. The blurb on the back cover says it will take us onward from Newton and address our place in the Universe from astronomical, physical, chemical, biological, philosophical, and social perspectives — again with the emphasis on the process of how we learn, rather than simply presenting the current status of known facts. The aim is to show science not as a sequence of stepwise linear developments but as a creative process with many missteps, wrong turnings, and misunderstandings along the way; but always with the understanding that the scientific method is the underpinning procedure that ensures that these errors and missteps are ultimately corrected by new evidence or fresh interpretation, to maintain a coherent scientific account.

With slightly different aims to the first volume there is, in this second volume, necessarily quite a bit of brisk restating of the scientific advances covered in the first, and it isn't until about Chapter 8 (of 26) that we leave behind the brief recounting of the ancient discoveries. It should be noted that if you really are a novice at much of this basic astronomy you might find the pace at which it is presented in Volume 2 rather rapid. The author points out to instructors intending to use the book as course material that it is advisable that students cover the first book before attempting this second. However, for the general reader Volume 2 is a stand-alone book and it thus covers pretty much the entire history of human scientific discovery — no mean feat in just 344 pages; and the author is well placed to attempt such an undertaking. He is an astronomer/astrophysicist who has made significant discoveries and contributions to the understanding of planetary nebulae and to the production of complex organic and pre-biotic molecules in the atmospheres of late-stage stars. The relevant parts of this work are described in this volume, particularly in the sections covering the origin of life. But most importantly in the context of this book he devised and presented the long-running (since 2010) Common Core Program of the University of Hong Kong on which this book is based. This course is presented to students from all faculties in an effort to ensure that all graduates leave the university with a basic understanding of the fundamental principles of how science works and to enable them to assess critically complex issues.

The topics are presented in 26 short chapters each with multiple sub-sections covering specific points, and each chapter ends with a brief review paragraph of what has been covered and a list of discussion points to think about in relation to the topics discussed. For example, the chapter on 'The Nature of Light and Matter' in just 16 pages, with nine subsections, covers (and I paraphrase the subsection headings): the elements, atomic theory, light and heat, the electromagnetic spectrum, heat and temperature, light as energy, the search for the ether, quantum theory, and science and utility. The list of ten questions to think about at the end of the chapter includes the philosophical significance of the chemical composition of air, and also the mind bending "How can you define something as real?" As the author points out in the preface, the object of these discussion topics is to motivate thinking beyond the immediate material in the chapter and explore the implications of the topics covered. He helpfully points out there is often no right or wrong answer.

In addition to the 26 chapters, which include a large number of diagrams and illustrations, there are as previously mentioned seven useful appendices, another 74 review or revision discussion questions, a detailed glossary of terms used, a reasonably thorough index, and a chapter-by-chapter list of further reading. So all in all there is a lot of sound useful material presented as straightforward but generally rather good educational text. But it must be remembered that this is one person's view of these essentials. What I found missing was the nuance that could have been provided by other voices, such as may have been offered by the original or review papers from which the information in this book has been derived. Other than the list of general further reading there are no references to the source material.

So this isn't an entirely uncritical review. Some of the explanations are a bit too brisk and unsatisfactory. Apparently the Apollo rock samples support the impact theory of lunar crater formation — we are not told how. We are told that the low density of the Moon indicates a lack of an iron core — we are not told how this density was measured. And the description of the ocean tides on Earth is very poor — with no explanation at all offered for there being two tides per day. In the last chapter, which is about the common themes discussed in previous chapters, and peripherally deals with the expanding Universe, there is the statement that the Universe is expanding in the fourth dimension of space — and we are told very little more about how we know this or even what that means to three-dimensional humans.

Despite these minor criticisms this book is a mostly excellent, carefully constructed, step-by-step educational path through the development of the process of doing science and resulting discoveries. Sun Kwok's book provides an all-embracing view of how science has enabled a detailed description of our place in the Universe — and I am sure the author would appreciate that having read it his students would also be able to turn their newly acquired critical abilities on to some of the contents of this book. — Barry Kent.

Small Bodies of the Solar System: A Guided Tour for Non-Scientists, by Hans Rickman (World Scientific), 2022. Pp. 222, 23·5 × 16 cm. Price £50 (hardbound; ISBN 978 1 80061 061 4).

The term 'Small Solar System Body' was recognized officially at the IAU General Assembly 2006 held in Prague, when resolutions were passed that provided a new definition for what makes a planet a planet, two consequences of which were that Pluto was assigned 'Dwarf Planet' status and the remaining celestial bodies, except satellites, categorized as 'Small Solar-System Bodies'. The author, Hans Rickman, a recently retired professional astronomer from Sweden, has adopted this concept for the title of his book, the subject of which encompasses not only all comets and minor planets but which includes meteors, meteorites, the hazards from near-Earth asteroids, as well as addressing the roles these small bodies may have played during the birth of our Solar System and the origins of life on Earth.

Rickman's career in astronomy from 1970 onwards makes him well qualified to write a book of this kind. It is very much a personal account, a compilation of events and anecdotes from his past and his professional involvement in many of the subjects tackled: as a result the book is an authoritative, accurate, and engaging account of 'small-body' astronomy. The writing style is a discursive one, presenting arguments for and against hypotheses in the way of a conversation with the reader, as opposed to merely presenting facts. It is a good example of science writing that will educate and inform the lay person. The contents comprise seven chapters tracking the history of each subject and where the current understanding has reached. One minor criticism is that the standard of English grammar and language can be patchy in places.

The book is rich in content and well worth a read not just by non-scientists but also by astronomers and others since it contains various nuggets of information that look to convey novel understanding of the subject. The hardback edition is physically well-made, a convenient size, and the paper feels almost archival grade in quality: a fine item for anyone's book collection. — Richard Miles.

Calculate the Orbit of Mars! An Observing Challenge and Historical Adventure, by Jane Clark (Springer), 2021. Pp. 316, 23·5 × 15·5 cm. Price £24·99 (paperback; ISBN 978 3 030 78266 5)

There must have been a number of 'lockdown' books written during the Covid-19 pandemic, and this is one of them. To read it is to trace the personal journey made by Dr. Jane Clark in determining — from her own backyard astronomical observations — the orbital elements of Mars. It is a book that can be followed by anyone who has taken A-level mathematics, albeit fully understood only if they have read the subject for at least a year at university. It is unusual to find a book aimed at this particular level. (Spherical trigonometry reminds one of H. R. Mills and his delightful book *Positional Astronomy and Astro-Navigation Made Easy*, but that was decades ago, and with simpler mathematics.)

The orbit of Mars has been refined on and off during the past century, and it is necessarily an on-going process. One recalls the classic papers written in the early 1900s by Percival Lowell about the axial tilt of the planet, and the refinements by Gérard de Vaucouleurs (during the 1960s to '80s) of its orbital elements generally. Modern ephemerides still differ slightly: comparing the JPL, BAA *Handbook*, and WinJUPOS versions will show differences in Martian central-meridian longitude amounting even to a few tenths of a degree.

I very much liked that the author qualifies all her factual claims and provides clear proofs of the formulae. For instance, there is a nice geometrical proof of one of the well-known spherical-trigonometry formulae, instead of the vector proof one tends to come across if you search for one on-line. But do not expect a formal textbook. The author has a fluent style, with funny digressions now and then. ("I have lived in places, like King's Lynn, Norfolk… where it is so flat that they have to look hard for somewhere to include a hill start in the driving test." Don't worry, it is a relevant remark.) Again, it is very much a personal journey.

We begin with early attempts at measuring planetary orbits, and to read the book is to follow the lives of those astronomers who were the real trailblazers: Tycho Brahe and Kepler, for example. This was fascinating for me, for in the Czech Republic I have stood at Tycho's tomb, seen the locations he observed from, and visited the places where Kepler lived. The author is clearly an adept mathematician, and she offers many insights into the personalities and their mathematics. Gradually we see how she obtained her own precise measurements of RA and declination during the period 2009–2020 by comparing digital images with star maps, and how she used them to derive orbital elements. Each step along the path is clearly explained, with the many pitfalls pointed out, lengthy computer programs revealed, and all the results summarized. There are many clear illustrations and diagrams. Final comparisons with the best modern ephemeris shows that she did remarkably well. A final investigation was carried out to see how well Tycho Brahe's 1582–89 data (corrected for precession) might compare with her deduced Martian orbit.

With desktop publishing one does not expect many errors in transferring the author's mathematical copy to the printed page, and I could casually find just a few typographical errors and two misnumbered references. (Back in 1978, Mr.

Mills was not nearly so fortunate… .) Appendices discuss polar coordinates, vector multiplication, and a proof of trigonometric addition formulae for all angles. There are many references and a good index (which oddly lists Brahe under T).

In summary, this is a unique text, and represents a rare piece of individual research and writing that has much to commend it. I must also praise Springer for having undertaken to publish such an unusual work. If you enjoy a mathematical challenge it will be well worth your while to obtain, whether you just skim through the text or follow all the mathematics to the final conclusion. — Richard McKim.

Kappa Distributions. From Observational Evidences via Controversial Predictions to a Consistent Theory of Nonequilibrium Plasmas, edited by Marian Lazar & Horst Fichtner (Springer), 2022. Pp. 330, 24 × 16 cm. Price £119·99 (hardbound; ISBN 978 3 030 82622 2).

Every physics undergraduate is taught that the distribution of particle velocities in a gas in thermodynamic equilibrium is given by an isotropic Maxwellian distribution $f_M \sim \exp(-v^2)$, where vector $\boldsymbol{v}$ is a velocity normalized to a characteristic speed proportional to the square root of the temperature. Both *in-situ* and spectroscopic observations show, however, that other than in the cool dense plasmas characteristic, *e.g.*, of planetary ionospheres where particle–particle collisions usually dominate the physics, charged-particle-velocity distributions in heliospheric and magnetospheric plasmas are never of this form, and are not therefore in thermodynamic equilibrium. For such hot, dilute, collisionless plasmas the ion and electron velocity distributions are generally approximately Maxwellian in the lower-energy 'core' containing the majority of particles by number, while at energies above a few 'thermal' energies a 'suprathermal' population dominates of power-law form that may contain comparable kinetic energy density. Analysing low-energy (~100 eV – few keV) electron fluxes in the Earth's magnetosphere observed by the *OGO-1* and *-3* spacecraft over fifty years ago, Olbert and Vasyliunas were the first to model such distributions using 'kappa' velocity distributions of the form $f_\kappa \sim (1 + v^2/\kappa)^{-(\kappa+1)}$, where $\boldsymbol{v}$ is again velocity normalized to a characteristic speed, and κ is an empirical constant best fitting the data. For small values of v such distributions approximate a Maxwellian, exactly so in the limit $\kappa \to \infty$, while for large values of $\boldsymbol{v}$, such distributions become power law $\sim v^{-2(\kappa+1)}$. The sixteen chapters of the present edited volume aim to summarize and review research over the past ~20 years concerning the origin and physical consequences of these kappa distributions, with exclusive emphasis on solar wind rather than magnetospheric plasmas.

The basic picture is one in which the plasma populations contain free energy (departures from isotropic Maxwellians) due either to the nature of the particle source, *e.g.*, electrons streaming along magnetic-field lines from the Sun into the background solar-wind plasma, or to the effect of subsequent transport in the large-scale fields of the system that can also produce field-aligned beaming and 'temperature' anisotropies. Such free energy then potentially leads to instability and the excitation of waves that augment spontaneous quasi-thermal emissions resulting from random particle fluctuations. Beaming, for example, may generate electrostatic Langmuir waves *via* the Landau resonance (incidentally the topic of this reviewer's first paper published in 1970), while 'thermal' energies perpendicular to the magnetic field that sufficiently exceed parallel energies for electrons and/or ions may lead *via* cyclotron resonances to excitation of whistler and/or ion cyclotron waves. 'Thermal' anisotropies may also excite 'hydromagnetic' (as opposed to resonant kinetic) instabilities, specifically the mirror instability for '$T_\perp/T_\parallel$'>1, or various branches of the firehose instability for '$T_\perp/T_\parallel$'<1. However, dispersion characteristics and instability conditions for both kinetic and 'hydromagnetic' modes may become significantly modified relative to classical results by the presence of kappa suprathermal particles, as discussed in several contributions to this volume. Analysis and computational modelling then show that these fields accelerate and scatter the ions and electrons to form slowly-evolving plasma systems with a significant suprathermal component, together with a self-consistent spectrum of waves and fluctuations. Methodology centres on application of the Vlasov–Maxwell equation set in both linear and quasi-linear approximations, with which it was a pleasure for this reviewer to become reacquainted *via* these more recent applications through perusal of this clear and well-produced monograph. — Stanley W. H. Cowley.

Physics of the Earth's Radiation Belts. Theory and Observations, by Hannu E. J. Koskinen & Emilia K. J. Kilpua (Springer), 2022. Pp. 272, 24 × 16 cm. Price £44·99 (hardbound; ISBN 978 3 030 82166 1).

The Earth's radiation belts were discovered over 60 years ago, at the beginning of the space age, but many questions remain regarding the relative importance of the physical processes controlling their behaviour. The inner radiation belt, which lies at equatorial distances of 1·1 – 2 R_E, is relatively stable, except during the largest geomagnetic storms. In contrast, the outer radiation belt, which typically lies at equatorial distances of 3 – 8 R_E, is highly dynamic. In this region the flux of relativistic electrons can vary by orders of magnitude on time-scales ranging from minutes to weeks. Understanding the variability of these so-called 'killer' electrons is important since enhanced fluxes can damage satellites and pose a risk to humans in space.

In this new textbook, Hannu Koskinen & Emilia Kilpua take us on an exploratory journey, using modern theories and observations, to document our current understanding of the physics of the Earth's radiation belts. It begins by giving us the tools to understand charged-particle motion in the Earth's magnetic field and how to describe the local plasma environment *via* particle distribution functions. In the basically collisionless medium of the Earth's radiation belts, changes to the particle distribution functions are largely controlled *via* interactions with plasma waves and we next learn about the important wave modes that pervade the various regions in the inner magnetosphere. We go on to find out about the drivers and properties of the relevant plasma waves before focussing on the effects of the waves on acceleration, transport, and loss of the particles themselves. Finally, we learn about the overall structure and dynamics of the radiation belts and discover some of their idiosyncratic behaviour.

This is an excellent text book for both experienced scientists and for doctoral students and young researchers embarking on research in this exciting and developing field. It is well written and presented, with figures from the latest satellite missions, and includes a comprehensive reference list for those who wish to pursue ideas further. While we have learned a lot about the fundamental processes governing the behaviour of relativistic electrons as outlined in this volume, there is still much to learn about how these processes combine to produce the variability that is observed. Ultimately, we need to understand and reliably predict the behaviour of outer-radiation-belt electrons, the latter being very important for satellite operators and engineers. This is a significant challenge for today's radiation-belt scientists and is likely to remain so for years to come. — Nigel P. Meredith.

Spacelab Payloads. Prepping Experiments and Hardware for Flight, by Michael E. Haddad & David J. Shayler (Springer), 2022. Pp. 520, 24 × 16·5 cm. Price £24·99 (paperback; ISBN 978 3 030 86774 4).

In the written histories of famous battles or military campaigns it is often the global overview by the leading commanders that is highlighted. The plans with maps of regiments described by curving arrows, the strategy and aims in bold font; only rarely do your hear from "the poor bloody infantry" slogging through the mud and bullets. A similar story — without the mud and bullets — could be told about the campaign to develop and use *Spacelab*. *Spacelab* flights were initiated during the early 1980s, a period in which NASA believed that the commercialization of space could be achieved by frequent flights of essentially a space trucking service using the Space Shuttle. Planning suggested two or three launches per month would be possible using a fleet of Shuttles — with each of the *Spacelab* elements having potential for about 50 launches. The "poor bloody infantry" in this case were the Level IV engineers and technicians charged with the task of assembling all of those payloads and testing the multitude of instruments in preparation for launch.

During the initial honeymoon period in which the ambitious aims were believed achievable, the infrastructure that provided reusable pallets and self-contained pressurized laboratories were developed. The system became known as *Spacelab* (a European name that replaced NASAs more prosaic Sortie Can or Sortie Lab). The planned launch schedule for *Spacelab* payloads required a massive increase in the number of instrument-integration engineers and technicians (Level IV). This was partly solved by making use of the Co-op scheme in which students could sandwich their university course work with work at NASA. This necessarily meant that the university course took longer than usual but for part of that time the students were getting an income. If they made a success of the Co-op work they were pretty much guaranteed a job after their finals.

Spacelab was a joint NASA and ESA endeavour which aimed to provide laboratory and observatory facilities in space. NASA would provide the Shuttle, Shuttle-critical crew, launch, and payload-integration facilities, and ESA would provide the *Spacelab* hardware and potential on-board scientists. The pressurized cylindrical laboratory module was provided by ESA through German aerospace companies, and the open pallet structures used both on *Spacelab* and many other Shuttle missions were designed and built in the UK by British Aerospace. The instruments and experiments were provided by international teams and institutions led by a notional Principal Investigator (PI). During this initial period there was a concerted attempt to make space flight accessible to as wide a range of users as possible. To this end it was also believed that at least some of the humans on board the shuttle would no longer need to be super-fit test-pilot types but could be any reasonably healthy individual — leading to another British contribution in the provision of three candidate payload specialists for the *Spacelab 2* flight. Two US citizens ultimately got that gig and one of them, John David Bartoe, is extensively interviewed in this book to give his side of interacting with the Level IV organization for that mission.

The system to be followed for *Spacelab* was that specific hardware, designed to be accommodated in the Shuttle's vast payload bay, would be filled with experiments and observatories provided by the US and ESA states and indeed other countries. The task of the Level IV team was to prepare these instruments from the various teams and institutions, attach them to this specific *Spacelab* hardware, and test and align them as required — that is, to do everything from receiving the instruments from their home institutes and making them ready for space flight and ensuring that they would operate according to the requirements of the instruments' PI, without jeopardizing the operation of the Space Shuttle. An incredible level of trust was thus required on both sides. The PI institute was required to trust their meticulously designed, developed, and tested instrument to a contingent of NASA employees — to hand their precious cargo over to the NASA team, many of whom were unqualified students still at university. The NASA team would then install it in the *Spacelab* laboratory or on pallets. Equally the NASA team had to trust the PI institute to obey the rules of providing safe instruments and support hardware to the Shuttle — a spacecraft in which human lives would be at risk if something hazardous were included in the instrument. Neither side of the equation started out with any expertise in the other side's technical know-how. Frequent communication across language and cultural difference was essential for the system to stand any chance of working. And there were indeed cultural differences — the authors point out that in some cultures "yes" does not necessarily imply agreement, merely that "I have heard what you have said and will think about it." On the other side there used to be the half-joking comment among some UK scientists: Question: "How can you tell when an American is working?" Answer: "He is walking and talking and has a mug of coffee in his hand". There were certainly cultural differences.

After an extensive overview this book details each of the *Spacelab* payloads in turn, and the particular circumstances of the Level IV work in each case. A story from *Spacelab 3* was new to me and involves the use of live animal enclosures for two squirrel monkeys and some rats. The animal enclosures were designed to ensure that animal waste products would be contained within the chamber. However, during the flight a design flaw became apparent and the resulting unconstrained debris circulated in the generality of the lab-module environment. An unnamed ground controller tried to convince the on-board mission specialist not to worry as the particles he could see were probably not pellets of faeces but more likely uneaten food particles. The astronaut in question, Bill Thornton, had grown up on a farm and in no uncertain terms explained that he knew what he was talking about. Another example of astronauts really knowing their sh**.

In spite of the cultural misunderstandings of international teams working with NASA in sequential partnership, it did all mostly work. Twenty-two *Spacelab* missions were flown between 1981 November and 2000 February. The UK-built pallets continued to be flown on several Shuttle missions after *Spacelab* operations were closed down. The authors give us a warts-and-all account of the difficulties of assembling components that looked fine in the drawings yet didn't physically fit when combined with other instruments and cable and cooling-systems runs. Differences of opinion as to which side of the payload/pallet interface was at fault were strongly expressed. Finally, when official strategy collided with reality, the programme was drastically curtailed and the number of launches significantly reduced. The *Challenger* disaster did much to reset the ambitious flight schedule and caused a reassessment of the work for a lot of the NASA Level IV engineers. Those who did not lose their jobs, when McDonald Douglas won the contract for payload ground operations, were reassigned to tasks such as refurbishing the offices — installing computers and ethernet cabling, *etc.*: as one commentator wryly notes, from electronics engineer to cable-TV installer. Other commentators note that much useful forward planning work to improve support for payload integration was also carried out.

In spite of all the documentation and conformance checking, frequently some extemporization was needed to get everything together. If an instrument didn't work first time the 'Jiggle test' was tried — it is horrifyingly exactly as it sounds. Or if an instrument's attachment holes didn't line up with pallet attachment points, then just "match drill" some new holes — I don't know of anywhere in the UK space-instrument teams where such a cavalier attitude would have been accepted. The Duke of Wellington, on surveying his troops before a significant battle, is supposed to have remarked "I don't know what effect they have on the enemy but by God they scare me". Seeing a Co-op NASA Level IV engineer with a spanner in one hand and a power drill in the other, any PI about to have his treasured instrument integrated into *Spacelab* may well have thought that Wellington had a point.

Although this is a long and very detailed book, often reading like a user's manual, with chapters, for example, describing the buildings at the Kennedy Space Centre (KSC) — including dimensioned drawings — the overwhelming need to communicate is always present.

After 2000 December the remaining Shuttle flights, until the system was terminated in 2011, were primarily in support of assembly and resupply for the *International Space Station*. *Spacelab* had long since given way to Space Station. However, this book really is the voice of 'the bloody infantry' of *Spacelab*; the participants in Level IV tasks clearly want their voices to be heard — and this book is a 520-page proclamation in response to perhaps having being overlooked. In essence it is a sustained cry of "Look at the astonishing things that we achieved and isn't that incredible" — and, yes, quite frankly it is. Haddad & Shayler have done a good job in getting the original voices of this dedicated team out into the public domain and as such have provided a valuable service to the history of space flight. — Barry Kent.

Perseverance and the Mars 2020 Mission: Follow the Science to Jezero Crater, by Manfred von Ehrenfried (Springer), 2022. Pp. 258, 24 × 16·5 cm. Price £27·99 (paperback; ISBN 978 3 030 921170).

This is the story of the *Perseverance* rover and its little helicopter, *Ingenuity*, told by Manfred "Dutch" von Ehrenfried, who has written a number of previous space-exploration books for Springer. The idea of carrying a helicopter to Mars dates back to 2012, when plans for the mission were at an early stage. The book is devoted to the story of how *Perseverance* — a more complex successor to *Curiosity* — got built and got to Mars, and what it did there.

The book opens with a discussion of mission objectives. In fact there are four: geology, astrobiology, sample caching, and preparation for the future human exploration of Mars. We learn the function of the various components of *Perseverance* and the stages of its launch, flight, and landing. The instruments are described in detail. Landing-site criteria required an astrobiologically relevant, geologically diverse, and ancient environment. Moreover, it had to have high potential for significant water resources (including hydrated minerals) for possible future human exploration. Jezero was only one of several possible landing sites, and it made a good final choice.

Lying below the Martian zero-datum level, Jezero was well placed to have been a lake filled with water in the geological past, and it incorporates a river delta. It lies to the north of the impact basin Isidis. (Your reviewer wishes to add that the Isidis basin has often been the focus of local and regional Martian dust storms, and during northern spring and summer it is crossed by the aphelion belt of water-ice cloud, so it is also an interesting location from a meteorological point of view.) The rover will be steered towards those sites on the crater floor most likely to yield clues as to whether life might ever have existed upon Mars. Chapters 5 and 6 were the most interesting for me, detailing the surface operations by *Perseverance* and the flights of *Ingenuity*, respectively.

The author describes the book as being a handy quick reference, and it is: the main text ends at page 164. We are spared the tedious recollections of conversations at conferences and in JPL labs and tea rooms that some other authors are so fond of. Nearly 500 persons were responsible for bringing ideas to the drawing board, to the factory, to the launch pad, and, ultimately, to the surface of Mars.

The book concludes with several Appendices covering the Mars Exploration Program and a useful Glossary. In Appendix 3 the author offers us a long list of brief biographies and portraits of the 2020 mission team. In Appendix 6 we find the dates of the various sample caches and the many helicopter flights, right up to the end of 2021.

At the time of writing, this mission is still underway. The cached rock samples may be returned to Earth later. Until then, Martian meteorites remain the only pieces of the Martian crust available for direct study in terrestrial laboratories. — Richard McKim.

Cosmochemistry, 2nd Edition, by Harry Y. McSween, Jr. & Gary R. Huss (Cambridge University Press), 2021. Pp. 437, 26 × 20·5 cm. Price £79·99 (hardbound; ISBN 978 1 108 83983 9).

Cosmochemistry? The authors of this fine survey, now in its second edition after 11 years, recognize cosmochemistry as "the study of the chemical compositions and its constituents, and the processes that produced those compositions." "A tall order to be sure", they add. This book restricts the emphasis to chemistry of objects in the Solar System including planets and satellites, asteroids, interplanetary dust particles, lunar samples, and pre-solar grains. Chemistry is the key tool linking the measured composition of an object to an understanding of its origin and evolution. Yet, this restricted scope for cosmochemistry calls for an understanding not only of chemistry but also of physics, geology, astronomy, and even biochemistry. *Cosmochemistry* should appeal especially — I do hope — to senior undergraduates and research students in the sciences seeking to work in a broad and growing field where breadth of intellectual interests can bring rewards to the individual scientist.

Cosmochemistry's early chapters copied from the book's first edition provide concise coverage of relevant nuclear physics, stellar nucleosynthesis, and determination of the composition of the Sun. Of particular note are several pictorial presentations of the Periodic Table (Figures 1.2, 1.3, 2.6, and 3.14), each annotated to enhance points made in the text. An advertised feature of this new edition is the inclusion of "focus boxes covering basic definitions and essential background material" with one box in these early chapters headed 'Cecilia Payne Cracks the Spectral Code'. Her appreciation that hydrogen (H) is the dominant element in stellar atmospheres fully deserves a 'focus box'. Dominance of hydrogen is far from obvious by casual inspection of the solar spectrum. I was disappointed that the text does not explain how the strength of a solar absorption line of element X is dependent on the abundance ratio X/H as a result of a line's strength dependence on the ratio of line to continuous opacity, with the latter largely set by the negative hydrogen ion. Precise determinations of the H content of stellar atmospheres not obviously deficient in H — the vast majority of atmospheres — is a contemporary challenge!

Cosmochemistry includes several topics far beyond the reach of investigators just a few decades ago. Indeed, the reach of experimenters in the decade between editions has required expanded coverage and reorganization of several chapters. Among the more mature of these experimental explorations is the study of pre-solar grains in which discovery of minute diamonds goes back to 1987. Now, McSween and Huss in their Table 5.1, 'Known types of presolar grains', name 14 types of grains. Their chapter offers a clear discussion of how pre-solar grains are isolated and investigated from primitive asteroids. Effective illustrations of cosmochemistry's reach beyond the Solar System are mature discussions of how pre-solar grains have proven to be probes of stellar nucleosynthesis, particularly investigations involving isotopic ratios and element ratios rarely accessible to stellar spectroscopists. Much has been learnt particularly about nucleosynthesis by AGB stars and supernovae. This continues to be a growing field so I look forward to the discussion in *Cosmochemistry*'s next edition which, as its two preceding editions, will reflect all significant developments in this field.

If asked to identify the field of stellar or Galactic astronomy which has grown fastest in recent years, most astronomers would reply "exoplanets". *Cosmochemistry* incorporates a brief discussion of exoplanets under 'Inferring the Compositions of Exoplanets' at the concluding section of their chapter on 'Cosmochemical Models for the Formation and Evolution of Solar Systems'. Note the plural 'Systems'. May we anticipate observational — principally infrared — spectroscopic investigations of exoplanets to reveal the diversity of routes by which exoplanets have formed.

Perhaps I may recall my initiation as a junior cosmochemist. I was observing at Mt. Wilson in 1968 when I was summoned to the telephone in the Monastery. This was a call from Professor Urey, "one of the fathers of cosmochemistry" (see Fig. 1.7 in *Cosmochemistry*). Urey wished to discuss my then-recent redetermination of the solar photospheric abundances of C, N, and O. I was surprised that my research into solar abundances had attracted Professor Urey's attention such that he wished to track me down off the CalTech campus. This and other interactions with senior colleagues across the field of cosmochemistry — broadly defined — expanded my interests in field.

Cosmochemistry deserves a wide distribution as a text for undergraduate and research students. Indeed, the book is worthy of the American Astronomical Society's Chambliss Astronomical Writing Award given for textbooks at either the upper-division or graduate level. — David L. Lambert.

Supernovae, Neutron Star Physics and Nucleosynthesis, by Debades Bandyopadhyay & Kamales Kar (Springer), 2022. Pp. 207, 23·5 × 15·5 cm. Price £89·99 (hardbound; ISBN 978 3 030 95170 2).

The title of this reasonably slim volume, which is published in the Springer *Astronomy and Astrophysics Library* series, accurately reflects what's included (if not what's left out). 'Supernovae' is dealt with in a single chapter entitled 'Theory of Supernova Explosions' (concentrating on the explosion physics, and not, *e.g.*, stellar evolution). 'Neutron Star Physics' gets two chapters: 'Neutron Stars' (very much concerned with theoretical matters, such as equations of state) and 'Binary Neutron Star Mergers' (similarly paying little more than a passing nod to observational matters, notwithstanding acknowledgement of multi-messenger astronomy). A final chapter, on 'Synthesis of Heavy Elements in the Universe', addresses what it says on the tin (while strongly focussed on the *r* process).

The authors appear to be primarily nuclear/particle physicists (most of their published output is in the mainstream physics literature), albeit with clear astrophysical interests. Perhaps because of this, the level of content seemed to this journeyman astronomer to veer from (occasionally) the condescendingly near-trivial, to (mostly) the narrowly and esoterically technical and mathematical. This in turn left me struggling to identify what readership might benefit from this monograph. The claim is that the book is "written for graduate students and researchers in the field of nuclear astrophysics"; having ploughed through most of the text (though very rapidly falling into 'skip the equations' mode) I'm not convinced. The tone didn't strike me to be particularly didactic, and I couldn't really see a clear development — each chapter is essentially a stand-alone, somewhat piecemeal review paper, with its own one-paragraph summary and extensive list of references to the primary literature.

The volume has evidently been prepared directly from a LATEX source file, with little or no rigorous copy editing, so that the typical presentational infelicities familiar to any thesis examiner are pervasive (careless mixing of text and math modes, incorrect dashes, quite a lot of idiosyncratic phrasing, punctuation, and grammar...); the use of a superscript zero in place of a proper (angular) degree symbol was a novel one for me, and initially confusing. There are plenty of line diagrams (scrupulously credited), a fairly detailed Contents page (although omitting the untitled Appendix which appears, without explanation, mid-way through the book), and a fairly cursory index. I sorely missed a glossary of the numerous abbreviations and acronyms. — Ian D. Howarth.

300 Problems in Special and General Relativity, With Complete Solutions, by Mattias Blennow & Tommy Ohlsson (Cambridge University Press), 2022. Pp. 354, 24·5 × 17 cm. Price \$22·99/\$29·99 (paperback; ISBN 978 1 00 901773 2).

Problems are the stuff of life in physics; the preface to one well-known textbook states it baldly: "the reader who has read the book but who cannot work out the problems has learned nothing". But students who sweat away at these things while cursing their professors probably fail to realize how hard it is to construct a good problem: neither too simple nor dishearteningly complicated, illustrating some important principle in a way that is amenable to a neat and elegant solution. So while books of problems are of course marketed at students, a lecturer of General Relativity (as I am) is bound to look at a text of this sort in the hope that there may be material that can ease the labour of delivering a course on relativity.

The bar is set quite high in this respect, with the astonishing 1975 collection of problems by Lightman, Press, Price & Teukolsky. That was a production of youthful exuberance, with all the authors between 1 & 4 years out from their PhDs. The present book is a rather more sober affair, being based on 20 years of teaching at the Stockholm KTH Royal Institute of Technology (although a little research indicates that the authors have not been presenting the courses there for as long as that).

Comparing the two sets, I would say that the new book feels a little more terse in its style of question, which can often be single technical issues (*e.g.*, recast the Schwarzschild metric from the common polar-coordinate form into

Cartesian coordinates), expressed as a single block of undifferentiated text. This is certainly the style of question that I grew up with, but something different is required for modern undergraduates (at least in the UK). Today, I find myself setting tutorial questions that offer rather more hand-holding, dividing a single topic into many sub-parts and guiding the student through the derivation with hints. This has the advantage that the different elements of the problem can be related, so that students feel the benefit of deriving a particular result when they get to apply it later on. Some of the questions in this book are of this form, but I feel the volume would have been improved if more of the material had possessed this 'through-composed' aspect.

Such a change might also have helped the book compete with Lightman *et al.* in their stated aim: "to awaken the reader's curiosity". The older book somehow communicates a sense of excitement about the subject, which I didn't feel to the same extent in the newcomer. Of course, I am not the intended reader, and students may very well be glad of the focus on individual technical challenges. But as an aid for student self-study, I feel the structure of the book could have been made more welcoming: Lightman *et al.* group their problems into 21 chapters of material under various subject headings, each chapter starting with some appropriate tutorial orientation. But in Blennow & Ohlsson there is a single introductory overview, much concerned with notation, with the problems then presented in a single stream. These are grouped by topic, but there is nothing to soften the transition between topics. Overall, then, this collection of material would suit the stronger students who already have a fairly good overview of the subject and who want to test their understanding *via* specific technical challenges. But relativity is studied by many more-average students, and these probably need a little more help in order to get the best out of the questions in this book. — John Peacock.

Applications of General Relativity, by Philippe Jetzer (Springer), 2022. Pp. 209, 24 × 16 cm. Price £59·99 (hardbound; ISBN 978 3 030 95717 9).

The full title has "With Problems" appended. The three middle chapters each end with a few pages of problems; the solutions at the end of the book take up thirty pages. In contrast to many books, the problems and solutions are very similar to the main text. I recently reviewed[1] a book[2] in these pages with the title *General Relativity: The Essentials*, which is probably the 'easiest' book on relativity I have reviewed, concentrating on the essential concepts. The subtitle would be appropriate for Jetzer's book as well, but in a completely different sense: this book is one of the hardest. It is not a textbook, but rather a compendium of, as the title says, applications of General Relativity (GR) (gravitational lensing, stellar structure, Shapiro delay, geodetic precession, gravitational waves, black holes, a tiny bit of cosmology — so all to do with astronomy and astrophysics), useful for someone who knows the material but wants to look something up, refresh their memory, *etc.* Equations are derived, but much is assumed. As such, it is somewhat like a much expanded and updated version of an old article I recently came across[3]. It takes very much a 'maths first' approach, the Einstein equation appearing already on p. 4 as opposed to p. 483[4,5]. The first and last chapters, without problems, are a very compact introduction to GR and a brief survey of tests of the theory; the other three are about various applications, gravitational waves and the post-Newtonian approximation, and black holes. The breadth of topics covered is thus smaller than in some other books, but the depth is great. I am familiar with Jetzer, a professor of physics at the University of Zurich, from his work in gravitational lensing, and that topic takes up somewhat more room than one might expect (but still just a few pages).

There are many books on GR and many good books on GR; I've reviewed just a small fraction in these pages. The main differences concern emphases and levels of difficulty; the same holds for this book — it is perhaps less mainstream than most, but in a good way. It is based on the author's lecture notes and it is clear that he knows the material and presents it well; footnotes provide additional clarification and each chapter has a list of references; a few diagrams, some using a bit of colour for clarity, are scattered throughout the text; there is a two-page small-print index. My only complaints are that better native-speaker editing is needed and the common 'misprint' of "Lorentz" for "Lorenz" when referring to the gauge (note that the Lorenz gauge is Lorentz invariant!). But those should not greatly hinder those who use the book as intended; it is very specialized, but fills an interesting niche. — PHILLIP HELBIG.

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(2) C. Rovelli, *General Relativity: The Essentials* (Cambridge University Press), 2021.
(3) D. L. Block, *QJRAS*, **15**, 264, 1974.
(4) J. B. Hartle: *Gravity*: *An Introduction to Einstein's General Relativity* (Cambridge University Press), 2021.
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High Energy Astrophysical Neutrinos, by Debanjan Bose & Subhendu Rakshit (Springer), 2021. Pp. 67, 23·5 × 15·5 cm. Price £49·99 (paperback; ISBN 978 3 030 91257 4).

The cosmos sends us information by photons (discovered some time before the year zero by a planarian named Ooze), cosmic rays (Victor Hess, 1912), gravitational waves (a *LIGO* group so large that the first author is Abbott with two B's, from 2015), a few bits of Moon rock (Apollo astronauts, 1969–72), and neutrinos (Raymond Davis Jr., sometime before 2002 when he shared the Nobel Physics Prize for the discovery). In this context, MeV neutrinos from the Sun and the sort that arrived in 1987 February from a supernova count as low-energy. High-energy neutrinos are the sort detected by the *IceCube* array at the South Pole under the stewardship of Francis Halzen. Such neutrinos interact mostly *via* deep inelastic scattering on nuclei, *via* either charged-current or neutral-current interactions. This book is probably for you only if all those words already made sense, and indeed the authors' preface says they are writing for graduate students who already have some exposure to astrophysics, particle physics, and quantum field theory. The first two detected *IceCube* events came from neutrinos of 1·04 and 1·14 PeV, leading up to a 2013 paper, the name of whose first author Aartsen, suggests an even larger team than the *LIGO* one. Not perhaps quite true, but it really does take a village to detect a high-energy neutrino.

The volume, with a 38-page introduction, seven pages on sources of TeV and PeV neutrinos (of which my favourite is the TED event of p. 56*), and 21 pages on neutrino detection on Earth has climbed perilously close to the witching

*You might think that some recorded TED talks have reached these exalted energies, but in fact TDE, Tidal Disruption Event of a star that has ventured too close to the supermassive black hole at the centre of an active galaxy is meant. There are anyhow no typographical errors after page 67, though a remarkable number before, for instance, the "proto-type experiments undergoing in the Mediterranean Sea" on p. 66.

price of $1 per page. There are definitely things to like about the book. The authors are good about citing original references, so you will meet Fermi, Breit and Wheeler, and Greisen, Zatsepin, and Wolfenstein in Chapter 1; Čerenkov, Frank, and Taam in Chapter 3 (though only year, journal name, volume, and page numbers, not the titles of articles or anything about the people). And there is a lovely picture of the *ANTARES* detector (about 40 km off-shore from Toulon, France) that includes what seems to be a large fish with a beam of light coming out of its mouth.

So, lots of numbers, details of detectors, equations leading to cross sections, plots of those cross sections (and a few of the Feynman diagrams), good discussions of some of the uncertainties (*e.g.*, concerning nature, source, and all, of the ultra-high-energy cosmic rays), but I could wish that some of those blank six pages at the end could have been used to list and decode every acronym, so the reader would not need to chase back a couple of pages to be reminded that PMNS is the Pontecorvo–Maki–Nakagawa–Sakata mixing matrix or back more than a couple decades in memory to the last conference where not everybody in the audience knew that an EAS is an extensive air shower. — VIRGINIA TRIMBLE.

The Sky is for Everyone: Women Astronomers in Their Own Words, edited by Virginia Trimble & David A. Weintraub (Princeton University Press), 2022. Pp. 472, 24·5 × 16·5 cm. Price £25/$29·95 (hardbound; ISBN 978 0 691 20710 0).

The Golden Age of Astronomy in the sixty-odd years just passed had seen much greater equity than the decades before that, with women astronomers contributing to a wide range of astronomical topics and even getting credit for it! Henrietta Leavitt for Cepheids and Annie Jump Cannon may have made major discoveries 100 years ago, but were considered 'computers' (at the Harvard College Observatory, since females would work for lower salaries than males). Some interesting group photos remain, including a 'paper dolls' of mostly women side-by-side as well as groups at work (https://hea-www.harvard.edu/~fine/Observatory/computers.html) that included Antonia Maury — one of whose collateral descendants turns out to be a Harvard–Radcliffe '63 classmate of mine; I even once asked a 'Jump' working at Williams College if she was related to Annie Jump Cannon, and she was.

Cecilia Payne-Gaposchkin, I learned from the book, got her PhD from Radcliffe since Harvard wouldn't give PhDs to women in the 1920s. (I note that the book under review omits periods from "PhD"; I have often seen a mention that she had the first Radcliffe PhD but without an explanation of why.) Since 'Mrs. G.' was a full professor of Astronomy and Chairman (as we then called it) of the Astronomy Department at Harvard when I was an undergraduate (we used to call it "freshman") in 1959, and since I had two female cousins who were at Harvard Law School in 1961, it didn't seem odd to me to have a female professor (though I subsequently learned that my cousins were two out of about 15 females, compared with over five-hundred men at the time). 'Mrs. G.' was indeed a formidable character: tall, with a British accent, and chain-smoking (she ultimately died of lung cancer), she stood out in any crowd. For figuring out that stars are almost entirely made of hydrogen and helium rather than terrestrial- and planetary-type materials that had so many spectral lines in the Fraunhofer spectra of stellar photospheres, she wrote in 1925 what was in 1962 called, in a book on the history of 20th-Century astronomy, "undoubtedly the most brilliant PhD thesis ever written in astronomy." Still, it took a few years, and some calculations from my mentor Donald H. Menzel to convince everyone — especially Henry Norris Russell at Princeton, then the most influential American astronomer — that she was correct. And her promotion to professor was listed for 1956, without specific mention that Menzel became Director of the Harvard College Observatory then, and considered her promotion a necessary thing to do as soon as he got the power.

A marquee name among the three-dozen essayists is Jocelyn Bell Burnell, the discoverer of pulsars. But even she pulls her punches in this essay, not including the story I have heard that she was excluded from the discussion of what would go into the announcement scientific paper, until she happened by her advisor's office and found a meeting on that subject under way. It was astonishing to read that, given the choice of that time, of further schooling from age 11, girls at least in her part of northwestern England had to have higher marks to carry forward, since they were known to be more mature than boys at that age, "to give the boys a chance". How fortunate we all are that her father brought home a popular book on astronomy that wound up inspiring her. Jocelyn (shall we call her Prof. or even Prof. Dr. Bell Burnell?) gave the best description of 'imposter syndrome' I have seen — and others in the book had it, too — "Clearly Cambridge had made a mistake admitting me; they would discover their mistake and throw me out. I decided my best policy was to work my very hardest, so that when they threw me out I would not feel guilty — I would know that I had done my best and was not good enough for Cambridge." Anyway, we now know that her best was plenty good — and that Dame Jocelyn's later career would have had longer tenures rather than just looking for jobs near the ones her husband took up.

The essayists are all with PhDs in the last sixty years; of the 37 essays, I found that I had heard of the work of the ones with PhDs before 2000 and not of the five since. [The publishers provide a list of all contributors on their web site for the book. — Ed.] Of course, the essays are a selection by the editors. And they (presumably mostly Prof. Trimble) listed many more women PhDs and their accomplishments in Chapter 1, though at least one qualified female teaching at a college rather than a research university was omitted. The introductory chapter starts with the earliest female astronomers, citing Catherina Elisabeta Koopman (1647–93), better known to us as Elizabeth Hevelius, with her work on the star catalogue of 1687. Of course, Caroline Herschel (1750–1848), arguably the first woman to get paid for doing astronomy (when the King of England gave her "Brother" (as she referred to him) William a stipend to move from Bath to Slough to be closer to him for the ability to show off the sky and telescopes after dinner) is mentioned. I wish our current Vice-President, from her official lodging at the US Naval Observatory, would show up for evening star-gazing.

Trimble and Weintraub (no mention is made of how that pair teamed up) start with "In France, Dorothea Klumke (1861–1942) earned her Docteur-ès-Sciences at the University of Paris in mathematical astronomy in 1893. She later married Isaac Roberts, and I am pleased to be a recipient of the Klumke–Roberts Award of the Astronomical Society of the Pacific, whose Wikipedia list includes several female names whose essays would have fit right in to this book."

We learn about Catherine Cesarsky's successes with instrumentation in the infrared and then as director of several institutions, including the European Southern Observatory and now in charge of the committee responsible for the Western Australia part of the *Square Kilometre Array* and a French government high-level advisor. And Sandy Faber, recipient of the Shaw Prize and a major figure in saving the *Hubble Space Telescope* from the disaster of its wrongly-shaped mirror, was in our graduate-school class but had advisors elsewhere, for reasons I learned in her essay.

During my year at the Institute for Advanced Study in Princeton, my wife and I got to know John and Neta Bahcall. I was interested to read how her career, somewhat roundabout *via* the Space Telescope Science Institute, went through overlapping research and administrative stages, winding up as Professor of Astrophysics at Princeton University, as deserved, including the directorship of the Undergraduate Programme in Astrophysics.

A 'Further Reading and Additional Resources' essay at the end of the book includes a paragraph about each of four-dozen additional woman astronomers, as well as a selection of articles from the essayists. Six books for children about our essayists, suitable for grades 3 to 9, are also listed, a nice touch. The book ends with a 10-page index. The list of abbreviations and acronyms at the beginning of the book is useful.

Princeton University has done a handsome job with the book, including (at least) a couple of black-and-white photos in each chapter. Though I admired the photo at the top of the front cover for its beauty as laser beams shot upward from the twin *Keck* telescopes on Mauna Kea to the Milky Way, only by reading inside did I learn that observing at the time was Andrea Ghez, who shared in a recent Nobel Prize in Physics for her work in weighing the supermassive black hole Sgr A* ("A-star" in the constellation Sagittarius) by using Kepler's laws of planetary orbits as expanded by Isaac Newton (years before he was knighted, so not 'Sir Isaac' then; Jocelyn Bell Burnell is the only person in the book of that rank), and as modified by Einstein.

With so many essayists, as even the blurbs on the back of the dust jacket make clear, the contents of the chapters vary greatly in the percentages of personal life, spurs to become astronomers, and scientific discussions that are included.

Without hesitation, I highly recommend this book of essays about astronomers, which could whet the appetite of students from high-school through post-doctoral ages to go into astronomy research, management, administration, or other aspects of our science. — Jay Pasachoff.

The Two Lives of Cheng Maolan: From the "French Silk Road to Astronomy" to the Meanders of Mao's China, by Thierry Montmerle, Yi Zhou & Yves Gomas (Springer), 2022. Pp. 116, 23 × 15 cm. Price £34·99 (paperback; ISBN 978 3 030 99929 2).

Cheng Maolan is now considered a 'Chinese hero'. An astronomy and technology museum was built and named after him in 2018, in his native city of Boye, Hebei Province, China. The museum features a tall, white statue in front of the building according to the back cover of this volume, which tells the story of how Cheng (otherwise Tcheng Mao Ling) achieved this status, after an exceedingly complex and chaotic career and life. A common phrase throughout the book is "very little is known about ..." (various periods of his life, typically), but what is known or reconstructed is a fascinating read.

First about the physical book: It is indeed 'brief', the more so as many of those 116 pages include images — of people, places, documents, maps, monuments, and telescopes, some in colour (which is probably reflected in the price). Most of the people mentioned have their names given in both the old Wade–Giles transcription (Mao Tse Tung, for instance) and the current pinyin transcription (Mao Zedong, for instance). Many names and also titles of books, documents, and such also appear in proper Chinese characters, and a few in both traditional and simplified versions of those characters. One of my goals in reading *Two Lives* has been to add to my modest repertoire of Chinese characters (the one that means China, and also occurs in the word for neutron star), perhaps the character for Mao or observatory?

Now about the human being: Cheng Maolan was born in 1903 or 1905 in Boye county, Hebei province, in a China still nominally ruled by the last Qing emperor, Puyi. Cheng made his first 'long march' to France in 1925, where he earned a couple of B.Sc. certificates, having been admitted to the Institut Franco-Chinois de Lyon in 1932, one of seven out of 473 IFCL students who achieved PhDs in astronomy. Cheng completed his thesis on the spectrum of Gamma Cassiopeiae (a star also studied by Margaret Burbidge and Vera Rubin under very different circumstances) in 1939, under Jean Dufay. Cheng remained at Lyon, observing at the new Observatoire de Haute Province (OHP). At OHP we also 'meet' Evry Schatzman and David Belorizky, Jewish astronomers at risk in occupied France, who had been offered refuge there with their families, by associate director Charles Fehrenbach. Well, I told you it was a chaotic story.

Cheng, duly elected to the IAU, though I think the year given, 1954, may be wrong, returned to China in 1957 July, participated in the Moscow IAU General Assembly as one of seven "*membres et hotes*" from "Chine", following which he was a member of Commission 21 (*Luminescence du Ciel*) and 29 (*Spectres Stellaires*).

Cheng's Chinese address was the wonderfully-named Purple Mountain Observatory, not, however, a wonderful site for a large research optical telescope that higher authority had decided China should have. Much of the subsequent site-surveying, which occupied seven years, was under Cheng's direction. That period included the Great Leap Forward of 1958, the subsequent famine (Cheng had already experienced surgery for tuberculosis back in France after WWII), and the Sino–Soviet split of 1960. The original requirements for the site — at least 1000-m elevation, less than 100 km from Beijing, and excellent seeing — may have been an impossible combination, with additional difficulties presented by the official desire that the planned 2-m telescope be entirely of Chinese manufacture.

The Xinglong Observatory occupies one of the sites Cheng had surveyed. It is about 100 km north-east of Beijing, at an altitude of 950 metres, and was inaugurated in 1989 November. Meanwhile, as it were, the Cultural Revolution occurred starting in 1966 May. It is not certain whether Cheng Maolan may have been physically persecuted or sent away into the country to do farm work, but he in any case lost power and position, and a new national observatory was no longer a government priority. By the end of 1972, the observatory was back on the agenda, and Cheng was officially appointed Director of the Beijing Observatory in 1976, near the end of the Cultural Revolution. There was time for some limited contact with French and American groups visiting China and for a bit of progress on educational initiatives that Cheng had pioneered soon after his return from France. But Cheng died on 1978 December 31, before even the dome of the 2·16-metre Xinglong telescope was completed. It was his nephew, Cheng Baohuai, who had known Chinese President Xi Jinping when they were both low-level officials, who pushed for the establishment of the memorial museum in Boye county. It opened in 2018 August.

Conflict-of-interest statement: I had the opportunity to read this work at an earlier stage and made (why are you not surprised?) an assortment of suggestions to the senior author. Some of them were taken — an explanation, for instance, that the second character in the name of Cheng's mother (Song Shi) on his identity document did not represent a given name, but just meant that she was a married woman.

However, the capsule life of Li Heng, another of the IFCL astronomy students, still has him at Princeton in 1948 (yes), writing papers with Lyman Spitzer (yes) and Karl Schwarzschild (no).

And in triumph, I share my second Chinese character: it reads "shan", means "mountain", and looks like the business end of a three-prong pitchfork, pointing up. — Virginia Trimble.

Understanding Gravitational Waves, by C. R. Kitchin (Springer), 2021. Pp. 413, 23·5 × 15·5 cm. Price £24·99/$34·99 (paperback; ISBN 978 3 030 74206 5).

Gravitational waves (GWs) are one of the most exciting predictions of Einstein's theory of General Relativity (GR). The present work (available in both paperback and e-book; to the extent that they may differ, this review is of the former) attempts to outline the basic science of GWs in a non-mathematical manner. The author has written this book to be accessible to a wide range of readers, from "people who have vaguely heard of gravitational waves somewhere or other and now want to know a little more, to amateur and even professional astronomers and astrophysicists whose specialisms lie elsewhere than with gravitational waves". To this end, the author has placed more advanced material in separate 'tutorials' and 'boxes', marked with one, two, or three stars to indicate their difficulty. Overall, the material covered and the manner of presentation are at a level somewhat higher than those of the typical popular-science book aimed at the 'interested lay reader'. There are lots of numbers, but no equations.

After a brief opening tour of the first binary-black-hole-coalescence GW event detected by the *LIGO* collaboration in 2015, the book turns to an historical introduction to our concepts of gravitation. This material is broadly similar to that in many other popular books, but again with somewhat more technical detail presented. The presentation of Galileo's investigations of free-fall is particularly clear, and includes nicely chosen quotes from Galileo's own writings. The presentations of Special and General Relativity are of modest length, and may prove harder for those in the book's intended readership to assimilate.

The book then moves to its central core: the experimental detection of gravitational waves. After a chapter on resonant detectors ('Weber bars'), the author describes modern laser interferometers for GW detection in surprising detail for a popular book. The reader who follows this discussion will learn about Fabry–Pérot cavities, mirror suspensions, mode cleaners, shot noise, and many other topics. The book also describes all the major GW detectors currently active, as well as many projects planned or under-development.

The writing is fluid, the physical book is nicely typeset and very readable, and I noticed only two outright errors. [For the record: Figure 5.14 and its caption are quite misleading, and the visible-light analogy is unlikely to be understood by the book's intended readership. And the statement that knowing the Newtonian gravitational constant ("big *G*") was essential for Neptune's discovery is simply wrong — the celestial mechanics in question depends (only) on knowing the product of *G* and a solar or planetary mass, not on knowing *G* alone.] The author introduces his own somewhat idiosyncratic system for naming detected GW events, but this is clearly explained and not a problem. The book refers to scientific notation as "index notation" and uses it throughout. SI units are used in almost all cases.

However, there are a few aspects of this book which are seriously lacking. First, the index is quite poor. Many technical terms are used in the book but do not appear in the index (*e.g.*, "ppm", "barycenter", "LISA", "radian", and "vignetting"). "pc" as an abbreviation for parsec is used in a number of places; it's explained in appendix D but neither "pc" nor "parsec" are in the index. The symbol ′ is defined in the text as "minute of arc", but the symbol ″ is used without definition; neither symbol (nor the corresponding terms) appears in the index. "Binary pulsars" is in the index, but the index entry lists two pages with no mention of the topic in addition to the page where the Hulse–Taylor binary pulsar is (very nicely) discussed. There are no index entries for "pulsar, binary" or "PSR B1913+16" (the formal name for the Hulse–Taylor system). $M_\odot$ is a peculiar case: it's in the index under "Sun, Mass symbol" for a page where it doesn't appear, but the symbol itself doesn't appear in the index, so there's no way to look it up if you don't already know that it has something to do with the Sun. It's not listed under "mass" either.

Second, the technical level of the material is rather uneven, and a disconcerting number of concepts are used without explanation. The overall level is generally suitable for a Canadian/American high school or 1st-year-university physics student, or perhaps for members of an astronomy club, but for such a readership I rather doubt the utility of citing post-graduate monographs such as those by Misner, Thorne & Wheeler (wrongly cited with only the first author's name); Poisson & Will; or Shapiro & Teukolsky. As another example, there are many nicely-printed time-frequency plots with colour-maps to show the nature of GW signals, but I didn't find any explanation of these.

Despite these oversights, I think many readers would enjoy and learn much from this book.— Jonathan Thornburg.

Millisecond Pulsars, edited by Sudip Bhattacharyya, Alessandro Papitto & Dipankar Bhattacharyya (Springer), 2022. Pp. 321, 24 × 16 cm. Price £54·99 (hardbound; ISBN 978 3 030 85197 2).

Time was when all of radio astronomy fit in a review article. Then it took a book (by Bracewell or Ginzburg and Syrovatskyy) and pulsars took a review article. A little later, pulsars took a book (by Lyne and Graham-Smith, a fifth edition of which, with a third, younger, author, has just appeared), and subsets of pulsars were *Annual Review* articles. Now just the millisecond pulsars need a whole book.

The present volume had its origins at a 2018 July scientific assembly of the Committee on Space Research (CoSPAR) in Pasadena, California, for which the present editors (the first two of whom are also chapter authors) had organized a session on millisecond pulsars. These are rapidly rotating neutron stars; the energy to be radiated can come either from spin-down (like ordinary Hewish–Bell pulsars) or from accretion of stellar material from a companion (like X-ray binaries), or occasionally both, in alternation. It is directed, the editors say, at "professional astronomers, graduate students, and other beginners."

The nine chapters come from 15 authors, nine with affiliations in Italy, three in India, and one each in the USA, Germany, and Spain. All are active contributors to the topics they discuss, in the sense of quite a few self-citations among the roughly 1300 references (not all different), adding up the totals from each chapter. Subjects of the chapters are reasonably clear (from their titles) and discrete (from their contents): (*i*) overview, (*ii*) X- and especially γ-ray emission, (*iii*) radio emission, (*iv*) accretion-powered X-rays, (*v*) nuclear-powered X-ray bursts, (*vi*) transitions between rotation and accretion power, (*vii*) origin and binary evolution, (*viii*) magnetars, and (*ix*) neutron-star equation of state and possibility of quark stars. Several chapters that provide numbers for how many of 'their' classes have been found (with field and globular cluster sources sometimes distinguished) are kind enough to provide web addresses where expanding catalogues are maintained.

My main frustrations are with the Springer-standard system of citations to references — superscript numbers, sending one madly to the end of every chapter to find out who and when [used also in these pages! — Ed.]. Some chapters have those references numbered in the order they occur in the text, others alphabetically (the worst to navigate, unless you mostly want to know whether you are cited). And the index is very skimpy. No listings of names unless they are part of a formula (Larmor), force (Lorentz), effect (Klein–Nishina), or theory (Yukawa). Many of your favourite pulsars are probably here (1913+16, the primordial binary, and 1957+20, the prototype black widow, of which more below) but they are not indexed. Ditto for glitches, fast radio bursts, and other things you might want to know about — discussed but not indexed. Two items I had not heard of before, redback pulsars and the Shklovskii effect, are indexed. The redback (spider) pulsars are akin to the black widows. The latter are binaries with brown-dwarf companions (less than 0·1 $M_\odot$), where the companion is being gradually surface-heated and evaporated away by the pulsar emission, and have been called black widows for decades. The redbacks have main-sequence companions of 0·1 to 0·4 $M_\odot$ (both sorts have orbital periods less than one day) and a large fraction of the current inventory were found by examining positions of otherwise unidentified *Fermi Large Area Telescope* gamma-ray sources, in radio surveys.

And then there is the Shklovskii effect, invoked in the chapter on transitional sources as a correction to spin-down rates, comparable in size to the effect of acceleration of the source in the Galactic gravitational potential; carefully indexed and twice mentioned in the relevant chapter, but neither defined nor referenced. The same authors do, however, provide a very nice diagram of binary MSPs in the orbital-period–companion-mass plane.

But if I could have only one page of this book it would be p. 89. It has a plot of the period–period-derivative plane, with points for all the kinds of sources for which both have been measured crossed by many straight lines (conveniently the axes are logarithmic) representing spin-down lifetimes (10^3–10^9 years), magnetic fields (10^8–10^{14} Gauss), spindown luminosity (10^{34}–10^{38} erg/s), and the 'death line' on which curvature radiation can no longer produce electron–positron pairs to radiate, with a dozen or so zombies. The diagram came from editor Alessandro Papitto, though it does not appear in his chapter, and for it, he and his colleagues from Mumbai and Pune can be forgiven much, the more so as none of them is probably responsible for either the indexing or the citation format! The price, at about 17 new pence per page, is even reasonable by Springer standards. — VIRGINIA TRIMBLE.

Public Astronomy, Los Angeles Style, edited by David DeVorkin and E. C. Krupp (Griffith Observatory, Department of Recreation and Parks, City of Los Angeles), 2021. Pp. 134, 25 × 37 cm (landscape format). Price $29·95 in the USA, $49·95 elsewhere (about £44) (softbound; ISBN 978 0 578 78941 5).

What would you think if somebody gave you a book with a cover photograph of a 9·5-inch Zeiss refractor, firmly mounted atop a 1932 Ford V-8? Clearly someone gone mad with PHOTOSHOP or a more recent equivalent? Well, no. David DeVorkin, senior editor and an author as well as historian of science at the Smithsonian Institution and fellow alum of UCLA, gave me this one, and the photo (though probably coloured) is real. It seems more probable because of increased expectation of weirdness, when you notice that the license plate reads lW 903, 19 CALIFORNIA 33. Yes, in those days you got a new license plate every year, and 260 000 was more than enough for all the cars in California. This one lived in Los Angeles (which then and now includes Hollywood, North Hollywood, and most of the San Fernanado Valley). It was part of a local astronomy-for-the-public programme (if that is not too organized a word). The telescope now belongs to Griffith Observatory, whose director, E. C. Krupp, is the other editor and an author. The car, a coupe (pronounced coop, like chicken), complete with dashboard, real hubcaps, and a canvas-wrapped spare tire perched on the rear bumper, has not been heard from lately. Krupp has a 1972 UCLA PhD earned under George Ogden Abell (who told your reviewer to go to Caltech when they didn't accept women students unless under "exceptional circumstances") on 'The Morphology of Rich Clusters of Galaxies', so we are all rather inbred.

The book had its origins in a special session on 'Making Astronomy Public: Los Angeles Style' organized by DeVorkin for the 221st meeting of the American Astronomical Society at Long Beach, California, in 2013 January. It took a while for the six speakers to write up their talks, but it was worth the wait! The other four authors are Tom Williams ('The early years of amateur astronomy in Los Angeles'), Lewis Chilton ('The Los Angeles Astronomical Society'), John W. Brigg ('Telescope Designer George A. Carroll'), and Anthony Cook ('Creating Griffith Observatory').

The earliest relevant photograph shows George Ellery Hale, John Muir, Andrew Carnegie, John D. Hooker (of the 100-inch telescope) and others in Pasadena in 1910. Colonel Griffith J. Griffith (1850–1919), whose bequest made the Observatory possible, appears on another page. Dr. C. W. Bush donated a 5½-inch Byrne refractor to a Southern California Science Association/Academy of Science in 1950. By way of temporal comparison Ishi (whose name meant 'Man' in his native Yana language), perhaps the last Californian indigenous hunter-gatherer, emerged near Oroville in 1911.

The Griffith Planetarium in Los Angeles was the third Zeiss-Jena installed in the United States (in 1935, after Adler in Chicago in 1930 and Fels in Philadelphia in 1934). Its distinctive characteristics were (*i*) the surrounding diorama of the Los Angeles sky line, behind which the 'sky' slowly darkened at the beginning of each planetarium show (the first delivered by Philip Fox, on loan from Adler, many by Dinsmore Alter the first Griffith director, and some by each of the editors of the present volume), (*ii*) seats that sort of slid forward while the backs tilted, permitting an easy look up, and (*iii*) an enormous black projector, shaped very much like a giant insect which emerged slowly from the centre of the floor as the sky dimmed, well suited to terrify small children in the audience (including me, several times). Subsequent renovations of the Planetarium (the second enabled by a large donation from Samuel Oschin, for whom the Palomar Mountain 48-inch Schmidt was also renamed) have improved the seating, removed the diorama, and replaced the lens-bearing insect with modern electronic gizmos, terrifying only if you have to program them.

There is still a Los Angeles Astronomical Society which continues to bring astronomy to schools, playgrounds, and street corners, though the separate North Hollywood and San Fernando Valley organizations have vanished. Future professional astronomer George Herbig (then a UCLA sophomore) makes a capsule appearance at age 20, claiming that Ras Algethi, with a diameter of 690 000 000 miles, is the largest star visible in the sky. And the *Long Beach Press Telegram*, in whose 1940 November 30 issue the relevant picture appeared, covered itself with standard press glory by declaring in the caption that "The young man ears [*sic*] his way by acting as guide and doing photographic work at the Griffith Municipal Observatory."

But to see what happened on total eclipse day (2017 August 21) and when the Space Shuttle *Endeavour* flew over Los Angeles (2012 September 21, not under its own power), you must acquire the book for yourself.

It is, of course, possible that your likely enjoyment of all this will vary as a negative power of your distance from Los Angeles, but I hope a very shallow power. — Virginia Trimble.

Other Books Received

General Relativity for Planetary Navigation, by James Miller & Connie J. Weeks (Springer), 2021. Pp. 104, 23·5 × 15·5 cm. Price £49·99/$69·99 (paperback; ISBN 978 3 030 77545 2).

A guide for astronautics in the vicinity of massive bodies, such as spacecraft travelling to Mercury.

Reading Terrestrial Planet Evolution in Isotopes and Element Measurements, edited by Helmut Lammer *et al.* (Springer), 2021. Pp. 445, 24 × 16 cm. Price £111·99/$169·99 (hardbound; ISBN 978 94 024 2093 7).

A collection of papers from *Space Science Reviews*.

The Tidal Disruption of Stars by Massive Black Holes, edited by Peter G. Jonker *et al.* (Springer), 2022. Pp. 589, 24 × 16 cm. Price £129·99/$139·99 (hardbound; ISBN 978 94 024 2145 3).

A collection of papers from *Space Science Reviews*.

More From The Library

A Cycle of Celestial Objects, Observed, Reduced, and Discussed by Admiral William Henry Smyth, R.N., K.S.F., D.C.L., Revised, Condensed, and Greatly Enlarged by George F. Chambers, F.R.A.S. of the Inner Temple, Barrister-at-Law. Second Edition (Clarendon Press, Oxford), 1881. Pp. 696 (plus Pp. 16 listing of other Clarendon Press books), 22 × 14 cm. Price not given; other Clarendon books listed from 3/6 to 18/6, but this one must have been much more difficult to typeset. Acquired by William Tyler Olcott of Norwich, Connecticut, in 1911 December. Purchased at auction as part of an assorted group of books once owned by Olcott from the American Association of Variable Star Observers.

The first edition of *A Cycle* was published in 1844 and dedicated, somewhat fulsomely, to "Sir John Frederick William Herschel, Bart., &c. &c. &. ... by his faithful friend, William Henry Smyth". So, what is it? A catalogue of about 1600 astronomical objects, arranged in strict order by Right Ascension, from $0^h\ 3^m\ 13^s$ to $23^h\ 59^m\ 13^s$, intended to be complete for interesting things visible in a typical 8-inch amateur telescope of the time, though Chambers explains that the Southern Hemisphere set (his main enlargement) is less complete than the Northern set, and likely to remain so, John Herschel having long since returned from the Cape.

For what equinox are the positions given? Chambers doesn't say, but explains that the positions have been precessed to 1890 and the precession constants are given for that year so perhaps also equinox 1890? Whatever his choice, it has put delta Cephei at R.A. = $22^h\ 25^m\ 5^s$ and Decl. N 57° 51′·1.

The analytical index lists all the catalogued objects by constellation, not quite our modern ones (Anser anyone? Antinous? Argo Navis has three parts: Carina, Puppis, and Vela.) As for the objects, much the largest group consists of double stars, with separation and position angle from several observers, and approximate visual magnitudes of the components They get promoted to binary stars if there is an orbit known. Ditto for the far less numerous triple and ternary stars. Other index terms are nebulae (including the Crab and Andromeda), planetary nebulae, clusters, globular clusters, star and comes, variable stars, red or crimson stars (most of these seem to be long-period variables, R Leporis, and so forth). Of the nebulae, I was most interested, of course, to read what the authors said about M 1. John Herschel and late Lord Rosse thought it resolvable into stars near the limits of their telescopes, while the author (not quite clear which one) saw it as a "milky nebulosity" rather than a cluster. The entry mentions it is close to Zeta Tauri, and indeed many of the catalogue entries include instructions for what is now, I think, called star hopping.

But we cannot say farewell to Smyth and Chambers without noting the rarest of the classes indexed, the temporary stars. Here are: (*i*) T Cor Bor (properly now T CrB) of 1866 May, described as undoubtedly a long-period variable, in whose spectrum Huggins saw both absorption features like those of the Sun and emission lines of gaseous origin. As the first of the recurrent novae, it is indeed in its way a long-period variable. (*ii*) 11 Vulpeculae, "the variable star observed by Anthelm in 1670", now CK Vul and, in various scenarios, a star–star collision, the merger of a binary white-dwarf pair, and to various observers in the 1850s and '60s a slightly fuzzy star at $m = 10$–12. (*iii*) Hind's new star of 1848 April, when it reached $m = 5$ or 4, now V841 Ophiuchi, and said to be still visible, "but is very small, say mag. 11" in 1880. (*iv*) Tycho's temporary star of 1572. A variable star at Tycho's (precessed!) position was thought to be the survivor (an opinion that appears elsewhere in old discussions of supernovae). This relic, just visible, is apparently the reason that SN 1572 was included in the catalogue, as supplementary object number 1602.

We have here, I think, the reason that Kepler's event of 1604, which was surely equally well known to the authors, does not appear. Neither do the events of 1783, seen by D'Agelet and Hevelius, or the 1843 outburst of η Carinae (recorded by J. Herschel), though entry 658 is eta Argus, with a long discussion of the appearance of the nebula, indexed as "Star and comes"; T Sco of 1860; and you must look for the antics of P Cygni (reported at $m = 3$ or 4 by Willem Janszoon Blaeu in 1600), in the discussion of χ^2 Cygni, itself a variable star with distant companions.

One last oddity, CK Vul was originally reported as "nova sub capite Cygni" because the constellations have moved, a point discussed in some detail recently in these pages (**119**, 272, 1999) by Roger F. Griffin, at least one of whose parents was a child at the time the 2nd edition of *A Cycle* was published. — VIRGINIA TRIMBLE.

ASTRONOMICAL CENTENARIES FOR 2023

Compiled by Kenelm England

The following is a list of astronomical events, whose centenaries fall in 2023. For events before 1600 the main source has been Barry Hetherington's *A Chronicle of Pre-Telescopic Astronomy* (Wiley, 1996). For the 17th–20th Centuries, lists of astronomical events came from Wikipedia and other on-line sources such as *Encyclopedia Astronautica*, supplemented by astronomical texts made available through the NASA Astrophysics Data System. Discoveries of comets, asteroids, novae, and other objects for 1923 appeared in the February issue of *Monthly Notices of the Royal Astronomical Society* in the following year. There were also references from *Popular Astronomy*, *Journal of the British Astronomical Association*, and *Publications of the Astronomical Society of the Pacific*. Professional discoveries and observations were followed up in *Astronomische Nachrichten*, *Astronomical Journal*, and *Monthly Notices of the Royal Astronomical Society*. Details of individual astronomers were supplemented by articles published in *Biographical Encyclopedia of Astronomers* (Springer 2007). Gary Kronk's *Cometography* Volumes 1–3 (Cambridge 1999–2007) provided details on all the comets. Finally NASA's Five Millennium Canons of Eclipses and planetary tables were consulted for information on eclipses and planetary events.

1923

January 8: Death of Hendrik Gerard Van de Sande Bakhuyzen. Born in 1838, he was a Dutch astronomer, Director of the University of Leiden Observatory (1872–1908), working on stellar parallaxes. He set a new standard for precision in making observations.

January 13: The Moon occulted Venus.

January 16: Birth of Michael John Seaton, British astrophysicist, studying the interstellar medium and the physics of stellar atmospheres, Professor of Physics at University College, London (1963–2007); FRAS 1953, FRS 1967, President of the RAS (1979–81), RAS Gold Medal 1990; died 2007.

January 30: Birth of James Wynne Dungey, a British space scientist, establishing the field of space weather and contributing to the understanding of plasma physics, FRAS 1950, Professor of Physics at Imperial College, London (1965–84), RAS Gold Medal 1990; died 2015.

January 31: Death of Walter William Bryant. Born in 1865, he was an assistant at the Royal Observatory, Greenwich (1892–1923), FRAS 1892, FRMetS 1906.

February 1: The Harvard College Observatory reported a nova-like variable in Sagittarius.

February 4: Death of Alfred Henry Fison. Born in 1857, he was a British lecturer in science at the Oxford University Extension College and writer of astronomical books, FRAS 1891.

February 7: Death of Edward Emerson Barnard. Born in 1857, he became a famous American amateur astronomer, discovering 16 comets, including three periodic ones (D/1884 O1 (Barnard 1), 177P/Barnard 2, and 206P/Barnard–Boattini). Then he worked at the Lick Observatory, discovering Jupiter's fifth moon Amalthea in 1892, and recorded numerous dark nebulae in the Milky

Way. In 1916 he found Barnard's Star, which had a very large proper motion and is one of the nearest stars to the Earth.

February 15: Milton La Salle Humason (Mount Wilson) discovered a nova close to the nucleus of the Andromeda Galaxy, magnitude 17·0 [Nova N22].

February 24: Death of Edward Williams Morley. Born in 1838, he was an American chemist, who worked with Albert Michelson to confirm the fixed speed of light (Michelson–Morley experiment).

February 27: The variable Mira reached an unusually bright maximum of 2·5.

February 27: Birth of Peter Howard Fowler, British physicist, studying cosmic rays with high-altitude balloons and aircraft, FRS 1964, FRAS 1967, FRMetS 1983; died 1996.

March 3: Partial lunar eclipse, visible from the Americas, Europe, Africa, and the Middle East [Saros 112].

March 4: Birth of Sir Patrick Alfred Caldwell-Moore, known to everyone as Patrick Moore. He was a British amateur astronomer and lunar observer, joined the BAA in 1934, FRAS 1945, a prolific writer of books on astronomy, presenter of BBC's *The Sky at Night* (1957–2012), Director of the BAA Lunar Section (1964–8, 1971–6), BAA President (1982–4), creator of the Caldwell catalogue of deep-sky objects, knighted 2001, Hon. FRS 2001; died 2012.

March 9: An L6 chondrite meteorite was seen to land near Ashdon, Essex, weighing 13 kg [Ashdon Meteorite].

March 17: Annular solar eclipse, visible as a partial eclipse from southern South America and Central and South Africa [Saros 138].

March 19: Death of the Reverend Samuel Runcie Craig. Born in 1844, he was an Irish amateur astronomer who observed Mars from his home observatory, FRAS 1890.

April 19: The Moon occulted Aldebaran in broad daylight, observed from the United States.

May 3: Death of Carl Albrecht Hartwig. Born in 1851, he was a German astronomer at the observatories of Strasbourg, Dorpat, and Bamberg, discovering comets C/1879 Q2 (Hartwig), C/1880 S1 (Hartwig), and C/1886 T1 (Barnard–Hartwig). On 1885 August 20 he discovered S Andromedae, a supernova in the Andromeda Galaxy [SN 1885A].

May 5: Carl Otto Lampland (Lowell Observatory, Flagstaff) discovered a 14th-magnitude supernova in the galaxy Messier 83 (NGC 5236). The supernova remained near magnitude 14 in May and faded to magnitude 15·7 in July [Supernova 1923A].

May 7: Joel Hastings Metcalf (Portland, Maine USA) reported that he had found a 9th-magnitude comet moving slowly near α Ophiuchi. Searches were made, but no comet was found.

May 8: Thomas David Anderson (Innerwick, East Lothian, Scotland) reported seeing a 5th-magnitude nova near 69 and 70 Cygni. No other observations were made, and the report is doubtful. Anderson, however, had discovered novae in 1892 and 1901 and was an experienced variable-star observer.

June: Hermann Oberth published privately *Die Rakete zu den Planetenräumen*

(*The Rocket into Planetary Space*), dealing with spaceflight and the use of orbiting space stations for weather monitoring, communications, and refuelling spacecraft.

June: Charles Pollard Olivier wrote a letter to *The Observatory* on the radiant drift of meteor showers, as the Earth moved through the meteoroid stream. This was at odds with the stationary radiants proposed by William Frederick Denning.

July 8: Death of Sydney Samuel Hough. Born in 1870, this British astronomer worked at the Royal Observatory, Cape of the Good Hope (chief assistant 1898–1907, Director 1907–23), FRAS 1899, FRS 1902.

Summer: A meteorite was seen to land in a field near Montferré in the Languedoc, France. It was eventually dug up in 1966 and found to be a stony H5 chondrite with a mass of 149 kg [Montferré Meteorite].

August 26: Partial lunar eclipse, visible from East Asia, Australia, and the Americas [Saros 117].

September 10: A total solar eclipse was visible along the coast of California and across Mexico and the Caribbean. The partial phase was visible from North and Central America. Many observatories sent expeditions to photograph the eclipsed Sun, but the weather was unusually cloudy [Saros 143].

September 14: Death of Giovanni Zappa. Born in 1884, he was an Italian astronomer at various Italian observatories, ending at the Collegio Romano in Rome.

September 20: Birth of John Everett Naugle, an American physicist, studying cosmic rays from high-altitude balloons, in charge of NASA's projects studying the Earth's magnetosphere; retired 1981, died 1993.

September 20: Death of Charles Burckhalter. Born in 1849, he was an American astronomer, Director of the Chabot Observatory, Oakland, California. He travelled to solar eclipses in California (1889), Japan (1896), India (1898), and Georgia USA (1900) and was founder member and President of the Astronomical Society of the Pacific.

September 26: Birth of John Ertle Oliver, an American geophysicist, who studied seismic waves, leading to support for plate tectonics; Professor of Geophysics at Cornell University, died 2011.

October 1: A meteorite was seen to fall near Serra de Mayé, Pernambuco, Brazil. Weighing 18 kg, it belonged to the rare eucrite class, which may have originated from the asteroid Vesta [Serra de Mayé Meteorite].

October 6: Alfred Harrison Joy (Mount Wilson) reported finding evidence of a companion star to the variable Mira, which was near minimum.

October 6: Edwin Powell Hubble (Mount Wilson) photographed the Andromeda Galaxy with the 100-inch. He noted on the plate a Cepheid variable, which he estimated as 900 000 light-years away (now 2·5 million ly).

October 12: Arturo Bernard (Madrid, Spain) discovered a comet while observing the variable U Monocerotis. He followed it as it moved rapidly southeast into Argo Navis. The comet was independently discovered by Alexander Dmitrievich Dubiago (Kazan Observatory, Russia), when it was magnitude 8. It was at perigee on October 18 (0·4075 AU) and was observed from observatories in the Southern Hemisphere. The comet reached perihelion on November 18 ($q = 0{\cdot}7778$ AU) and was last seen on December 8 [Comet C/1923 T1 (Dubiago–Bernard)].

October 14: Death of Arthur Alcock Rambaut. Born in 1859, this Irish astronomer became Astronomer Royal for Ireland (1892–7) and Radcliffe Observer at the University of Oxford (1897–1923), working on stellar positions; FRAS 1893, FRS 1900.

October 19: Robert Grant Aitken (Lick Observatory) visually observed the companion star to Mira.

October 21: First public showing of a planetarium projector at the Deutsches Museum, Munich.

October 27: The Moon occulted Aldebaran, observed from Britain.

October 31: Karl Reinmuth (Königstuhl Observatory, Heidelberg) discovered what appeared to be a comet in Pisces (mag. 13·4), which was given the temporary designation 1923b. Further images in November and December were stellar, and the orbit was similar to the Aethra group of asteroids. It was named (1009) Sirene and reached perihelion on November 30 ($q = 1{\cdot}4352$ AU). The asteroid moved slowly across Aries and Taurus and was last seen on 1924 February 26. Apart from one observation in 1940 September, the asteroid was not recovered until 1982 July. The asteroid may be the nucleus of an extinct comet [1923 PE = (1009) Sirene].

November 1: Robert Hutchins Goddard (Clark University, Worcester, Massachusetts) successfully test-fired a liquid-fuelled rocket motor on a test frame for the first time.

November 2–27: John Philip Manning Prentice (Stowmarket, Suffolk) observed enhanced activity of the Taurid meteor shower.

November 9: Harvey Harlow Nininger, an American biologist, observed a very bright meteor over Kansas, USA, which he searched for in vain. It inspired him to spend the rest of his life collecting and studying meteorites.

November 10: Periodic Comet d'Arrest was missed at its return in 1917 and a close encounter with Jupiter had made its orbit rather uncertain. Searches were made in the late spring and summer, but nothing was found. Then William Reid (Rondebosch, South Africa) found an 11th-magnitude object in Piscis Austrinus. The comet's position was confirmed in late November and recognized as comet 6P/d'Arrest. Searches of photographs found images on September 5 and 7. The comet remained faint in December and was last photographed on 1924 January 31 [Comet 6P/d'Arrest].

November 14: There was a newspaper report of a plan to build a telescope larger than the Mount Wilson 100-inch on Mont Salève in the French Alps. The project never materialized.

November 18: Birth of Alan Bartlett Shepard Jr, American test pilot and astronaut, member of NASA's Mercury Seven astronauts, pilot of Mercury–Redstone 3 *Freedom 7* in May 1961, becoming the first American into space, Chief of Astronaut Office (1963–9), commander of Apollo 14 in January 1971, becoming the fifth man to walk on the Moon; retired 1974, died 1998.

December 1: Birth of Douglas Reginald Bassett Saw, British chemist and amateur astronomer, making over 10 000 variable star observations; BAA member 1961, FRAS 1964, Director of the BAA Variable Star Section (1980–7); died 1990.

December 6: A very bright fireball appeared over Wisconsin USA.

December 12: Death of Hendrikus Johannes Zwiers. Born in 1865, he was a Dutch astronomer at the Leiden Observatory, working on stellar positions and calculating comet and double star orbits.

December 13: William Frederick Denning (Bristol, England) reported that the Geminid meteor shower was very active.

December 15: Hermann Oberth's book *Rakete zu den Planetenräumen* (*The Rocket into Planetary Space*) was published in Germany, inspiring a number of scientists and engineers to become interested in the study of rockets.

December 15: Birth of Freeman John Dyson, a British–American physicist and mathematician, covering a number of fields looking to the future. He looked into the future of space exploration and introduced the Dyson sphere (how space-faring civilizations could meet their energy requirements); died 2020.

December 21: A meteorite was seen to fall 10 km south-southeast of Nakhon Pathom in Thailand. This L6 chondrite meteorite weighed 23·2 kg [Nakhon Meteorite].

December 28: Death of Otto Julius Klotz. Born in Canada in 1852, he was a surveyor and geophysicist, surveying the Canadian–US borders. As an astronomer he was Director of the Dominion Observatory (1917–23); FRAS 1904.

December 31: Death of Jean-Marie Édouard Stephan. Born in 1837, he was a French astronomer, Director of the Observatory of Marseilles (1864–1907). He discovered asteroid (89) Julia in 1866 and the interacting galaxy group Stephan's Quintet in 1877. He also confirmed the discovery of comet 38P/ Stephan–Oterma in 1867.

A rare pallasite meteorite was found 1·5 km west-northwest of Newport, Arkansas, USA, weighing 5·6 kg [Newport Meteorite].

A weathered IIIAB iron meteorite was found 6 km northeast of Savannah, Tennessee, USA, during road construction. It weighed 60 kg [Savannah Meteorite].

A miner found a IIIAB iron meteorite near the silver mine Sierra Sandon in Antofagasta, Chile, weighing 6·33 kg [Sierra Sandon Meteorite].

While harvesting, a farmer found an IVA iron meteorite, weighing 11·5 kg, near Seneca Township, Michigan, USA [Seneca Township Meteorite].

1823

January 8: Birth of Alfred Russel Wallace. Known principally as an evolutionary biologist, he had interests in geodesy and astronomical causes for glacial periods. He disagreed with Percival Lowell's view of Mars, considering it a cold, lifeless, desert world; FRS 1893; died 1913.

January 26: A total lunar eclipse was visible from Europe, Africa, the Middle East, Asia, and Australia [Saros 121].

January 26: Death of Lieutenant-Colonel William Lambton. Born in 1756, he was a British soldier and surveyor, involved in the Great Trigonometrical Survey of India; FRS 1817, FRAS 1823.

January 27: Death of Charles Hutton. Born in 1737, he was a British mathematician and surveyor, Professor of Mathematics at the Royal Military Academy, Woolwich (1773–1807). He calculated the density of the Earth from Nevil Maskelyne's observations at Schiehallion in 1774 as 4500 kg m^{-3} (modern value 5515 kg m^{-3}), concluding that the Earth's core must be metallic with a density of 10 000 kg m^{-3}; FRS 1774, RS Copley Medal 1778, FRAS 1822.

February 11: A partial solar eclipse was visible from Siberia [Saros 147].

March 15: Periodic comet Grigg–Skjellerup reached perihelion (q = 0·7992 AU). Discovered in 1902 and recovered in 1922, it was only in 1987 that it was recognized as being identical to a comet observed by Jean Louis Pons in 1808 [Comet 26P/Grigg-Skjellerup].

March 25: Birth of John Ashton Nicholls, British amateur astronomer and lecturer on science to mechanics' institutions; FRAS 1849, died 1859.

April 11: Birth of Sandford Gorton, a British amateur astronomer, who was editor of the *Astronomical Register*; FRAS 1860, died 1879.

May 12: Birth of John Russell Hind, British computer at Greenwich and amateur astronomer, who discovered ten asteroids, including (7) Iris, (8) Flora, and (12) Victoria, deep-sky objects, and variable stars, including T Tauri, Nova Ophiuchi 1848, and U Geminorum; FRAS 1844, RAS Gold Medal 1853, died 1895.

June 9: Birth of Richard Dunkin, a British computer at the Royal Observatory, Greenwich (1838–47) who worked on the *Nautical Almanac* (1847–83); FRAS 1851, died 1895.

June 21: Birth of Jean Chacornac, a French astronomer at the Observatory of Marseilles, where he observed asteroids and sunspots and discovered comet C/1852 K1 (Chacornac); died 1873.

July 7: Birth of Per Magnus Herman Schultz, Swedish astronomer at Uppsala (1859–73), Professor of Astronomy and Director of the Observatory at the University of Uppsala (1873–88), measuring the positions of 500 nebulae despite long twilight and bright aurorae; Associate of the RAS 1882, died 1890.

July 8: A partial solar eclipse was visible from Northern Europe and North Asia [Saros 114].

July 19: Birth of Frederick Brodie, a British engineer and amateur astronomer, observing Mars, sunspots, and star clusters; FRAS 1855, died 1896.

July 22: Birth of Raphael-Louis Bischoffsheim, French banker and enthusiast for astronomy, who financed French observatories, especially at the Pic du Midi and Nice; FRAS 1881 and member of the French Académie des Sciences 1890, died 1906.

July 23: A total lunar eclipse was visible from the Americas, Europe, Africa, and the Middle East [Saros 126].

August 5: Birth of Father Alfred Wold SJ, British astronomer at the Stonyhurst Observatory, Lancashire, in charge of meteorological (1848–51) and magnetic (1858–60) observations; FRAS 1849, died 1890.

August 6: John Frederick William Herschel (Slough, Buckinghamshire) discovered the giant elliptical galaxy NGC 7010 in Aquarius.

August 7: A. Dinsmore (near Nobleborough, Maine, USA) heard what sounded like musket fire and saw a small whitish cloud spiralling earthward. Something struck the ground, which he dug up, finding a meteorite weighing 5 to 6 pounds (2·3 to 2·7 kg). It was a rare eucrite meteorite, which may have originated from the asteroid Vesta [Nobleborough Meteorite].

August 10: Heinrich Wilhelm Brandes and his colleagues (Wrocław, Poland) observed 140 meteors in less than two hours. This was an unusually bright display of the Perseid meteor shower.

August 21: Birth of Nathaniel Everett Green, British artist and amateur astronomer, drawing the Moon and planets; FRAS 1875; Director of BAA Saturn Section(1891–3, 1895–9) and BAA President (1897–8); died 1899.

September 4: Birth of Carr Waller Pritchett Sr., an American amateur astronomer, observed Jupiter's Great Red Spot in 1878; died 1910.

November 27: Birth of James Dyson Perrins, British amateur astronomer, local politician and promoter of education in Worcester, Worcestershire; died 1887.

December 1: Heinrich Wilhelm Matthias Olbers received a report from Johann Casper Horner that some Swiss hunters had seen a 'very obvious comet' in the west-north-western sky at sunset. No other observations were made, and the Great Comet at the end of the year was too close to the Sun to be visible.

December 29: A French surveyor, Eléonore Suzanne Nell de Breauté (Dieppe, France), discovered this comet in the morning sky. The following morning Jean Louis Pons (Marlia, Italy) found a bright, naked-eye comet in the morning, appearing as smoke from a chimney. He watched the comet nucleus rise with a tail 3 to 4 degrees long. It had already reached perihelion on December 9 ($q =$ 0·2267 AU) and was moving away from the Sun. The comet was independently discovered by a number of astronomers in the next few days. On 1824 January 5 it was magnitude 3 with a tail 5 degrees long. The comet remained a spectacular object during January. Then it faded steadily in February and March and was last seen on April 1 [Comet C/1823 Y1 (Great Comet)].

End of year: An L4 chondrite meteorite was observed to fall near Botschetschki, Sumy Oblast, Russian Empire (now Ukraine), weighing 614 g [Botschetschki Meteorite].

Cambridge University Observatory founded.

Heinrich Wilhelm Matthias Olbers proposed that, as the sky is dark, the stars could not be evenly distributed through infinite space (Olbers' Paradox). Other astronomers had previously considered this.

1723

January 5: Birth of Nicole-Reine Lepaute, a French astronomer, who calculated the orbit of Halley's comet for its return in 1759. She also provided planetary ephemerides for *Connaissance des Temps*; died 1788.

January 31: Birth of Petronella Johanna de Timmerman, a Dutch scientist, married to Johann Friedrich Hennert, Professor of Astronomy at the University of Utrecht, observed the great comet of 1744 and wrote the poem 'On the tailstar showing itself in the years 1743 and 1744'; died 1786.

February: Death of Samuel Watson. Born in 1651, he was an English clockmaker, constructing elaborate astronomical clocks for Charles II, as 'Mathematician in Ordinary', and for Sir Isaac Newton. In 1712 he intended to build a marine chronometer to solve the problem of longitude at sea but could not get the support of the Clockmakers' Company.

February 17: Birth of Johann Tobias Mayer, a German astronomer and cartographer, who produced a detailed map of the Moon; died 1762.

March 8: Death of Sir Christopher Wren. Born in 1632, he was an English architect, mathematician, and astronomer, Professor of Astronomy at Gresham College, London (1657–60), and the University of Oxford (1661–73), involved in the formation of the Royal Society, observed the Moon, Saturn, and comets; designed the Royal Observatory at Greenwich.

June 3: A total solar eclipse was visible from the East Indies. The partial phase could be seen from southeast Asia and the East Indies [Saros 123].

June 11: Birth of Johann Palitzsch, a German amateur astronomer, who recovered Halley's Comet on 1758 December 25; died 1788.

October 10: Chinese astronomers first observed an 'astounding star' below Canis Major in the morning sky. The comet was white and small with a one-degree tail. Ignatius Kögler (Peking, China) also discovered a 3rd-magnitude comet with a tail 4 degrees long. It was independently discovered by Crossat (Cayenne, French Guiana) on the 15th and William Saunderson (Bombay, India) on the 16th. The comet had been at perihelion on September 28 (q = 0·9988 AU) and was closest to the Earth on October 14 (0·1033 AU). The comet was widely observed from Europe in the second half of October, as it moved back into the northern skies. Many astronomers used long-focus refractors to study the comet's coma and nucleus. In November the comet was followed by Giacomo Filippo Maraldi, James Bradley, Edmond Halley, and George Graham. Bradley made the last observation on December 18 [Comet C/1723 T1].

November 9: Transit of Mercury, observed by Eustachio Manfredi (Bologna), Balthasar Mentzer (Hamburg), and Edmond Halley (Greenwich).

November 27: An annular solar eclipse across the Pacific was only visible along the west coast of South America as a partial eclipse [Saros 128].

An L5 chondrite meteorite, weighing only 39 g, was observed to fall near Ploschkovitz, Bohemia [Ploschkovitz Meteorite].

James Hodgson, nephew of Sir Christopher Wren, published *A System of the Mathematics*, promoting John Flamsteed's work.

George Graham discovered the diurnal variation in the Earth's magnetic field.

1623

January 10: A stony meteorite was observed to fall near Plymouth, Devon, with a mass of 10·4 kg [Stretchleigh Meteorite].

April 15: A partial lunar eclipse was visible across the Americas, Europe, Africa, and the Middle East [Saros 106].

April 29: An annular solar eclipse was only visible as a partial one from southern South America and South Africa [Saros 132].

June 19: Birth of Blaise Pascal, French mathematician and physicist, worked on conic sections and atmospheric pressure; died 1662.

July 16: A great conjunction of Jupiter and Saturn, only 5 arcminutes apart.

August 23: Birth of Stanislaw Lubieniecki, a Polish astronomer, who wrote *Theatrum Cometicum* (*The Theatre of Comets*), a three-volume account of comets; died 1675.

September 20: Wilhelm Schickard wrote a letter to Johannes Kepler, describing a Calculating Clock, an early mechanical calculator, which he had invented.

October 8: A partial lunar eclipse was visible from Asia and the Americas [Saros 111].

October 9: Birth of Ferdinand Verbiest, a Flemish Jesuit astronomer and mathematician in China, accurately predicting eclipses and reforming the Chinese calendar; died 1688.

October 23: A total solar eclipse was visible from southern North America. The partial phase was visible from North America and the Caribbean [Saros 137].

October 28: Birth of Johann Grueber, an Austrian Jesuit missionary and astronomer, travelling to China to support the Western astronomical community there. He returned overland through Tibet and India to Constantinople; died 1680.

October: Galileo Galilei published *Il Saggiatore* (*The Assayer*), a defence of the Copernican system and an attack on Orazio Grassi, who had proposed that comets were farther than the Moon, as Tycho Brahe had demonstrated with the comet of 1577. This publication would lead to Galileo being investigated by the Inquisition.

November 24: Japanese astronomers discovered a 'broom star' in the west after sunset, recorded in *Shiryo Sohran*.

December 24: Death of Michiel Coignet. Born in 1549, he was a Flemish mathematician, instrument maker, and cartographer, producing atlases and works on navigation.

Birth of Margaret Lucas Cavendish, Duchess of Newcastle, an English philosopher and poet, writer of the factual *Observations upon Experimental Philosophy* (1666) and the fictional *The Description of a New World, Called the Blazing World* (1666); died 1673.

Michael Maestlin published a revised edition of *Epitome Astronomiae* (*A Summary of Astronomy*), supporting the Copernican model of the Solar System.

(before) Birth of Jacques Buot, a French engineer, mathematician, and astronomer, who worked on fortifications and experiments in physics. He observed eclipses, comets, and the planets; died 1678.

1523

February 13: Birth of Valentin Naboth, a German astronomer, astrologer, and mathematician at the Universities of Erfurt and Cologne, before teaching in Padua; author of books on astronomy and astrology; murdered 1593.

July–August: The Chinese discovered a 'sparkling star' in the Hercules–Serpens–Ophiuchus–Aquila region, recorded in *Ming Shih* and *Hsu Wen Hsien Thung Khao*.

August 26: Copernicus (Frombork, Poland) observed a lunar eclipse, which he recorded in *De Revolutionibus*. The eclipse was total across the Americas, Europe, Africa, and the Middle East [Saros 120].

(about) Death of Ruy Faleiro, a Portuguese astronomer and geographer, who had prepared information for Magellan's expedition.

1423

May 30: Birth of Georg von Peuerbach, an Austrian astronomer, who observed the Sun, Moon, and planets, as well as Halley's Comet in 1456; died 1461.

October: 'Guest stars' were seen in the east and west, which combined and fell. Probably a bright meteor shower.

Birth of Muhammad ibn Muhammad ibn Ahmad Abu AbdAllah Badr Shams al-Din al-Misri al-Dimashqi [Sibt al-Maridiani]. He was an Arab mathematician and astronomer, a prolific writer of astronomical texts; died about 1495.

There was a 'sign' in the Sun seen from Russia and recorded in the *Chronicle of Novgorod*; a very large sunspot.

Jean Fusoris constructed an elaborate astronomical clock for the cathedral at Bourges.

1223

July: A comet was seen in the evening sky over France and was visible for eight nights. According to the *Chronicon Guillelmi de Noagiaco* it was seen to predict the death of the French king Philip II, who died on July 14.

August 28: The Japanese discovered a white comet in the northwest after sunset, recorded in *Dainihonshi*. The following night the comet had brightened and its tail had lengthened.

September 1: The Chinese observed Mars pass through Praesepe in Cancer.

1123

April 4: A meteor shower was seen before dawn from Germany, recorded in *Annales Casinenses*.

August 11: Korean astronomers observed a 'sparkling star' in the Plough, recorded in *Koryo-sa*. This may be the object seen from Syria, where "a great star appeared the length thereof was from south to north, and the width thereof was like the neck of a horse, and it was visible for two months."

1023

January 9: A lunar eclipse was seen from Ireland, recorded in the *Annals of Ulster*. The French historian Ademarus Cabannensis mentioned that the lunar eclipse was seen from Paris. The eclipse was partial across Europe, Africa, the Middle East, and Asia [Saros 89].

January 24: A 'large' solar eclipse 'at the 6th hour' was observed from

London, recorded in *Annales Blandinienses*. The eclipse was total only from the northwestern British Isles [Saros 115].

Autumn: Ademarus Cabannensis recorded that a comet appeared in Leo during the autumn. This would place the comet in the morning sky before dawn. The report is uncertain.

923

February 1: An aurora borealis was seen from France, recorded in *Annales St. Columbae Senonensis*.

June 1: A lunar eclipse was observed from Baghdad. Mid-eclipse occurred 1 hour 40 minutes after sunset. The partial eclipse was visible from Europe, Africa, the Middle East, and Asia [Saros 103].

November 11: Abu al-Hasan and Ibn-Amajur observed a solar eclipse from Baghdad. Mid-eclipse occurred while the Sun was 8 degrees above the eastern horizon, recorded by Ibn Yunus. The eclipse was total across the Middle East, India, and Southeast Asia [Saros 96].

November–December: The Chinese discovered a 'broom star' near θ, γ, and δ Cancri, recorded in *Thung Chien Kang Mu*.

823

February 19: Japanese astronomers saw a 'sparkling star' in the southwest after sunset, recorded in *Dainihonshi*. The comet remained visible for three nights.

523

December 20: Chinese astronomers recorded that Jupiter and β Scorpii were only about 12 arcminutes apart.

423

February 13: The Chinese discovered a 'sparkling star' to the south of Pegasus, recorded in *Sung Shu* and *Wei Shu*. It had a white tail 20 to 30 degrees long. The comet passed across Pisces and Eridanus and remained visible for 20 days. Marcellinus recorded that a comet was seen from the Roman Empire. Ichiro Hasegawa suggested that it might be an earlier return of Comet C/1931 P1 (Ryves).

December 13: According to *Sung Shu* and *Wei Shu* the Chinese discovered a second 'sparkling star' in Libra, with its tail stretching 40 degrees towards Arcturus. The comet moved east, and its tail increased in length, remaining visible for more than ten days. Marcellinus recorded that the comet was seen from the Roman Empire.

323

Kong Tong, a Chinese astronomer, constructed an armillary sphere with three rings and a sighting tube.

AD 23

Birth of Gaius Plinius (Pliny the Elder) in Northern Italy, a Roman military officer and writer, whose *Historia Naturalis* (*Natural History*) in 38 volumes covered a wide range of philosophy and science, including astronomy; died during the eruption of Mount Vesuvius in AD 79.

Death of Liu Xin. Born in about 50 BC, he was a Chinese politician, mathematician, and astronomer.

178 BC

December 23: A possible zero date for the Antikythera mechanism, coinciding with the New Moon, a solar eclipse, and the Winter Equinox. The eclipse was annular across the Middle East, including Babylon, South India, and Southeast Asia [Saros 58].

478 BC

February 17: Herodotus recorded a solar eclipse at the time the Persian king Xerxes was making his great expedition against Greece. The eclipse was annular across the Mediterranean, the Black Sea, and Central Asia [Saros 42].

1278 BC

November 22: Transit of Venus.

Here and There

A PRECESSION EFFECT?

... by finding its bright star, Arcturus, which is part of a pattern of stars, or asterism, called the Summer Triangle. — *New Scientist*, 2022 May 21, p. 51.

CLOSE INDEED

Solar Orbiter's next close perihelion will take place on 13 October, when it will be just 4·3 million kilometres (0·29 astronomical units) from the Sun. — *Astronomy Now*, 2022 July, p. 16.