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MEETING OF THE ROYAL ASTRONOMICAL SOCIETY

Friday 2022 November 11 at $16^h 00^m$
in the Society of Antiquaries Lecture Theatre, Burlington House

MIKE EDMUNDS, *President*
in the Chair

The President. Welcome everybody — this is a hybrid meeting. For those of you on-line, if you look at the top left of your screen you should see a small green shield. This symbol means that you are using the most updated version of Zoom and that it is secure. Questions can be asked at the end of the lecture, but as you are muted, please use the chat facility; if you're on-line, use the track facility to be able to ask your questions and then your question will be read out by Dr. Robert Massey, Deputy Director of the RAS, in the question session. We don't get that many questions on-line so we wonder if there's anybody actually out there.

We're now passing on to the programme today, and I'm very pleased to welcome Dr. Olivia Jones, who's going to talk about 'Early science with the *JWST*'. Some of you will have been to the specialist session today, which was chaired, in fact, by Olivia. I must say it was tremendously exciting, and very well run as well [applause]. Honestly, I just sat there enthralled at some of these new results, these pictures, and spectra — talk about a golden age. There was one quote, though, which I must share with you. Someone said "the Universe is amazing and beautiful". That was coming through these investigations. When we do our public outreach don't forget that. The Universe is an amazing and beautiful place, and here's a new way of looking at it, so I'm very pleased to introduce Olivia Jones. She is STFC Webb Fellow, based at the Astronomy Centre at the Royal Observatory, Edinburgh. She obtained her PhD from Jodrell Bank in astrophysics in 2013, then worked at the Space Telescope Science Institute, home, of course, of the *Hubble* and *JWST* missions, prior to moving to Scotland. She's an expert in infrared astronomy — the beginnings and ends of stellar evolution. She's currently a member of the *JWST* instrument team and was involved in supporting its launch, commissioning, and the first observations earlier this year. So, over to you and wow us all please.

Dr. Olivia Jones. We have spent the last day discussing *JWST* observations and there is a mountain of new science which is helping to re-write the textbooks as we go. To date 97 papers have been published on the high-z Universe alone.

The *JWST* has been in the news a lot. It is the biggest telescope launched into space with its deployable 6·5-metre mirror along with a telescope-sized sunshield which cools the telescope down so that it can work at infrared wavelengths. It is optimized for spectroscopy and we are seeing a whole new high-resolution view of the infrared.

The telescope was launched on Christmas Day 2021 *via* an Ariane rocket from French Guyana. The launch was pretty well perfect and leads us to believe that rather than have a 10-year mission we might expect to get 20 years plus of useful working operation. *JWST* operates between 0·6 and 28 microns and overlaps in wavelength coverage with both *HST* (0·9–2·5 μm) and *Spitzer* (3–160 μm).

Following the launch there were six months of intense activity by hundreds of people on the commissioning teams. Once the telescope was in space, the sunshield was deployed and the telescope was then located at the L2 Lagrangian point where the three parts of the primary mirror were opened and aligned. It then took 120 days for the telescope to cool down to its planned operating temperature and for science commissioning to begin.

My own research concerns galaxies: I have a galaxy 0·5 Mpc away in which I am interested and I have a PhD student working on it. An image from *Spitzer* shows a few of the brightest stars but many more are visible in the *JWST* image which will boost interest in stellar populations. Stars down to magnitude 28 can be seen. The *JWST* is not just about imaging. Using the *Near-Infrared Spectrograph* (*NIRSpec*) and pointing at a very dense field at the Galactic centre results in an image containing 200 stellar spectra.

JWST can observe objects ranging from the Solar System to the very first galaxies. There are three instruments which operate between 1 and 5 microns. These are *NIRSpec*, *Fine Guidance Sensor/Near-Infrared Imager and Slitless Spectrograph* (*FGS/NIRISS*), and *NIRCam*. The *Mid-Infrared Instrument* (*MIRI*) is an imaging instrument which has been specially cooled to 7K and is sensitive to the range between 5 and 28 microns, so it used for objects such as planets, comets, asteroids, warm dust, and protoplanetary discs. There are four main areas of research. Firstly: the end of the Dark Ages, first light, and reionization. We want to see the assembly and evolution of the galaxies — where do the metals come from? Chemical evolution of the Universe happens — galaxies are merging and smashing into each other and interacting and there is a lot of change happening. Closer to home we want to look at stars and proto-planets — how do the earliest stars form; how do massive stars form? These are all unanswered questions. We want to examine the atmospheres of the exoplanets but we also have beautiful images of Solar System objects including Jupiter showing the aurora.

Looking back at early spiral galaxies you can see star formation occurring. The amount of star formation varies throughout the Universe, but we want to be looking at galaxies further away, close to cosmic noon at $z = 2$, when most of the star formation happened. The chemical evolution of the Universe became more metal-rich. We can observe different chemical compositions and chemical-evolution models that go back to the very first stars and galaxies in the Universe. We have detected galaxies at $z = 17$ but this is an early and provisional result and I am sure that we could go deeper. Some time has been spent making 'deep field' images with much shorter integration times than with *Hubble*. We are seeing lots of red galaxies. What we want to look for are those galaxies which are very red and very bright in *MIRI* but not present in all filters in *NIRCAM*. A surprise has been that the [O III] line at 4363 Å in emission changes the field with abundance estimates at extreme redshifts. Of the three highest-redshift galaxies that we have found, one is very metal-poor. These are the sort of objects that people are looking for. We have taken images of Stephan's Quintet which is 13 Mpc distant and we can see individual stars. The *MIRI* image shows polycyclic aromatic hydrocarbons (PAHs) which are being pulled out into the intergalactic medium between the galaxies. These cannot be seen at all in *Hubble* images. One of the members of the Quintet has a black hole at the centre and spectroscopy reveals the metal abundance of the material falling into it. There are lines of iron, argon, neon, and sulphur in emission and in absorption lines of silicates due to small, sandy particles.

Observations of the transits of extrasolar planets using *NIRISS* — an example is WASP-96b — can detect the atmospheric composition of the planet. Between 0·8 and 2·8 microns there are several features due to water vapour in the atmosphere around the hot gas giant. A five hour *MIRI-NRS* spectrum has been obtained of the super-Earth L168-9b during a transit. Direct imaging in several wavelengths using a coronagraph has also revealed a planet orbiting HIP 65426.

With my interest in star formation, I have been very excited to see what images of the Pillars of Creation would reveal. With *MIRI*/*NIRCam* going to longer wavelengths the obscuring layers of dust can be peeled back allowing us to see the structure of the dust within. More PAH emission is visible but we still cannot see into the heart of the object. Red protostars show lots of features and there are CH_4, NH_2, and silicates in absorption. There has been a paper published on the protostar visible at the end of one of the Pillars. In the wavelength range 5–28 μm there are many features in absorption. This shows protostars in the early phase before they start to ionize their surroundings — they would not have been seen by *Hubble*.

Spectroscopy has also been done on the Cat's Eye Nebula (NGC 6543) and 3D structures start to appear, whilst imaging of the massive interacting WR binary WR140 shows a series of dust shells which are emitted every 8 years as the two stars reach periastron in a very eccentric orbit. At least 17 concentric shells can be seen in the image extending some 10 trillion km into space. *MIRI-NRS* has resolved two inner rings which appear to be composed of PAHs.

The people who made *JWST* work number about 20 000 over a period of 25 years. They come from 14 countries and 29 US states and involved 250 companies, agencies, and universities.

The President. Thank you very much. Questions?

Reverend Garth Barber. First of all, thank you for a fascinating talk. When you are looking at a galaxy at $z = 11$ just as a blob of light, how is the redshift determined? Do you get a spectrum that you can identify or is it a more general process?

Dr. Jones. This is not my area of science but what they do is to look at the imaging data on the object in many different wavelengths and then look for the Lyman-α break. This galaxy is not visible at the shorter wavelengths but at one wavelength it will just start to become very bright. The longer the wavelength that is, that will give you a quick idea of how far away an object is, and you can then use those data to model with template spectra exactly how bright these are in the feature wavelengths, and then by using the model and using priors in Bayesian analysis you can get an idea of the redshift and the properties. But whether they agree with each other is still a matter for debate, and it really does depend on calibration and systematics. This current early survey didn't find the same targets, but this one at $z = 17$ seems to be real, people agree on that one.

The President. A couple of questions on-line.

Dr. Robert Massey. There are three on-line, probably more to follow, and I'm also advised you have quite a lot of time for Q & A, but I'm looking at the Chair who'll probably put me right on that. The first one is from Ian Robson. I'll read it *verbatim* and he says "Brilliant stuff", two exclamation marks. "Do you know who was responsible for selecting the colour palette for the images, especially the galactic ones, to make them so beautiful?"

Dr. Jones. They are an awesome team at *JWST*. There is a team, I think, of at least three. There are videos on-line showing how they select the colour palette involved and it is to bring out the different features. They tend to work on the idea that the shortest wavelength is to the blue and the longest wavelength is to the red, so they keep that generally in mind. But the colour palette of how exactly they pick each filter is down to their skill. I have tried with my targets, the star-forming regions, which come in the same wavelengths, but I can't even get close. It's a great way of communicating the science to the public.

Dr. Massey. The next one is from John R. Hughes and he says he's interested in some brief comments from you about how the international teams agree access time and prioritize what to investigate with so much to analyze. It's maybe off topic, but just needs a brief answer.

Dr. Jones. It is probably coming onto topic soon: the *JWST* cycle-2 call will soon be out and that has come round faster than I'd like and so you can put forward a proposal to observe targets. It's based on the scientific merit of what you want to do. Anyone in the world can forward a target, along with a scientific justification for that, and then panels of experts from around the world in each field grant those proposals, and then allocate time based on peer review of how good they are and the resources it will take. It's a long process, and it's very competitive, but I think it brings out the best science.

A Fellow. My question too is about the colour palette. You know the wavelength of the light when it's received here and you also know the red shift. Would it not be possible to reproduce the wavelength as it was emitted? Of course with any image, you'd have to reduce it to just the visible spectrum emitted to make it meaningful to the eye, but could that be done and would it be worthwhile?

Dr. Jones. It won't be worthwhile. And why would you do it? These things emit in the infrared. They don't emit visible wavelengths, so it's meaningless to try and bring them to your eye. They're spectacular in the infrared. Leave them there.

The Fellow. It's not that a lot of the infrared is originally visible. That's what was in my mind.

Dr. Jones. No, they are bright in the infrared. That's where they all look spectacular. It's not the optical where they're spectacular, it's the infrared.

Dr. Massey. Stuart Eves is asking "To what extent does *JWST* evidence of galaxy structures in the very early Universe call into question the current Big Bang model?"

Dr. Jones. Pass.

The President. I think the short answer is it doesn't, yet.

Dr. Jones. We're in the early days. I'm not going to comment further.

Ms. Ahlam Abdi. Wonderful talk by the way. I wanted to ask, is there concern over the lifetime of *JWST* when we're concerned with space debris? We've already had one minor strike on the mirrors. I'm just wondering if it's an actual concern.

Dr. Jones. No, it's not a concern. We knew micro-meteorite strikes were going to happen. They've been modelled along the way, and it will be a limiting factor at some point, and probably for the coronagraphs first, but no, it's not a concern. Degradation is built into all the models and performance estimates.

The President. I hope this isn't one of those 'No, there's no hurricane' occasions. I'm presuming that the prediction is OK, but, keep your fingers crossed.

Mr. Christopher Taylor. How far away would the Sun and Jupiter have to be so that you could resolve Jupiter with *MIRI*?

Dr. Jones. I think we've observed with *MIRI*, and definitely with some of the other instruments, the structures in the aurora on Jupiter are visible.

Mr. Taylor. No, I mean if the Sun and Jupiter were an exoplanet system exactly like that of the Sun and Jupiter and exactly that distance apart, how far away could that system be and you could still resolve Jupiter from the Sun.

Dr. Jones. I'm sorry, I'm not an exo-planet person, they're not calculations I would know off the top of my head.

The President. Has anyone done the calculation in their head?

Professor Matt Mountain. Twenty parsecs.

Professor John Zarnecki. This is a comment rather than a question, and it's prompted by your last slide where you talk about people making *JWST*, and I'm reminded of Helen Walker who was a Fellow of this Society for many years, and if I remember correctly, she was the test-team leader for *MIRI*, and spent many months leading the team testing and calibrating *MIRI*. She spoke, I think, on the subject, to the Society, so it's a bittersweet occasion, really, because she died four years ago, and never saw the results of all her labours. It's good to remember all the work that she did, I think.

The President. Thank you, John. Anyone else on-line? While you're thinking of one more question, I was rather amused today to hear people saying "I'm looking at this redshift-7 galaxy and there are these $z = 2$ galaxies in the way. You know, I wish they wouldn't have all these galaxies at redshift 2 that get in the way", and it reminded me of Messier. As you know, Messier drew up his list of those annoying nebulae and galaxies that got in the way of discovering comets, so it's a nice historic parallel. Olivia, thank you very much indeed. [Applause.]

Now we move on to a set-piece lecture which I've been very much looking forward to — the James Dungey Lecture. James 'Jim' Dungey was a space scientist, I guess you'd call him. He was involved in plasma physics and died in 2015 and known particularly for his work on magnetic reconnection. The James Dungey Lecture is given annually on a suitable topic in geophysics, including solar physics, solar–terrestrial physics, or planetary science. This year, I'm delighted that Dr. Licia Ray is giving the lecture entitled 'From neither here nor there: the coupling between giant planets and their surroundings'. Licia Ray is senior lecturer in space and planetary physics at Lancaster University. Her research explores the coupling of planetary atmospheres to their surroundings, and in particular she's interested in the structure of high-latitude regions of the magnetosphere and how the planetary atmospheres exert control over magnetospheric, ionospheric, and thermospheric cooling. I think I got that right, just about. It's a great pleasure to welcome this year's James Dungey lecturer.

Dr. Licia Ray. [It is expected that a summary of this talk will appear in a future issue of *Astronomy & Geophysics*. Jupiter, the king of the planets, is visible to the naked eye in the night sky as a small dot. Yet its vast magnetosphere, if visible to the naked eye, would be larger than the Sun. The behaviour of this behemoth in our local neighbourhood is dictated by the interaction between the rapidly rotating planet, plasma generated from material ejected by the Galilean moon Io, and the planetary magnetic field that threads through both regions. I will discuss how Jupiter is coupled to its local surroundings and what roles the atmosphere, magnetospheric plasma, and the region in-between each play in the interaction. I'll touch upon how recent results from *Juno* have changed our understanding of the system and where to go next.]

The President. Thank you very much indeed for the splendid talk, beautifully illustrated.

A Fellow. Jupiter's main auroral ovals seem to be quite well defined and fairly constant, so what part of the magnetosphere are they coupled to, and what is the source of such intensity and position in those main ovals?

Dr. Ray. In terms of the radial range of the magnetosphere, it's probably around 20 to 35 Jovian radii, well within the middle magnetosphere. It's not near the edge. But that might vary depending on the local time sector, so it might be a little bit further out in the dawn region, a little bit closer in at dusk, and it will vary if there's a plasma-injection event, say, so if there's a lot of plasma that's come in from the tail, that can distort the currents, that can adjust the emission. If there's a large event on Io — if there's a massive eruption — you end up introducing a lot more mass that could bring the mapping of those auroral ovals in. And there has been one case where the oval has been seen to be coincident and sitting on top of Ganymede, which is at 15 R_J. So we can do a little bit with the moons and give us some information there, but actually understanding how to map auroral features out and doing that in a dynamic way is something that we really need to improve upon. Everything right now involves statistical representations.

Professor Steve Miller. It's good you've got that cartoon of the magnetosphere up there, because what you can see is, looking at the kind of a cut through noon to midnight, those field lines, loaded on the current sheet, as they swing round to the dawn-side — they're going to have to contract back in again because they're going to have to fit inside the magnetosphere properly; and I just wonder if there are some acceleration mechanisms that can be throwing some of these heavy ions up to higher latitudes where *Juno* is now seeing them, because I agree that wasn't expected?

Dr. Ray. The local time of those observations, because they were from early in the mission, was dusk. In order for them to be passing through, there would have been more dusk sector, and dusk sector has its own fun stuff, because as you move around from noon into dusk, you end up increasing the parallel energy of particles, and perhaps that's one of the explanations for that. So, you do end up with signatures. You're quite right, as the tail whips around and anything that's been stretched out has to then come within the confines of the magnetopause boundary through dawn. You will end up with acceleration of particles there and you will end up with bright dawn storms. If you lose the plasma and it's lost down the tail, then you also have an empty magnetic-field line that's rushing in. That can bring some hot, tenuous plasma back in with it, so I'm not sure if it'll explain those observations — probably worth a look.

Dr. Robert Massey. This is from Emma Bunce: "What future mission would you design to help understand this complex coupling scenario and test the next generation of models?"

Dr. Ray. Multiple spacecraft. We need at least four, preferably more. We'd really want something to measure electric fields, but that's just being greedy. You would need at least four spacecraft to give some comprehensive coverage. And actually at Earth we have four with *Time History of Events and Macroscale Interactions during Substorms* (*THEMIS*) and five with *Magnetospheric MultiScale* mission (*MMS*). Jupiter is a much bigger system, so you'd really want to have maybe 16. You could have four in each local time sector, and then maybe every now and then you could leave a local time sector alone. There is one other way though. One of my colleagues is Dr. Will Dunn at UCL, and one of his brainchildren is the *SMILE* (*Solar wind Magnetosphere Ionosphere Link Explorer*) mission at Earth. You know if we could get something like that at Jupiter, that might be quite nice, if you could image the magnetopause boundary, at least, and just get some visual TV-like response. But still, 16 minimum.

The President. How long, can I ask, is the *Juno* mission carrying on?

Dr. Ray. I think it goes through 2025, at the moment, the extended mission — is that right? That might be wrong. Might be 18 months.

Mr. James Salmon. Has *Juno* actually flown through any of the flux tubes from the moons?

Dr. Ray. Well, it's flown directly through a moon flux tube. I believe so, but I would need to double check. Will is nodding, so that's a good sign.

A Fellow. Has there been much thought about the historical evolution of Jupiter's magnetosphere? I realize that you're still trying to get the physics of the present magnetosphere, but has there been any thought about how it would have evolved historically? And for instance, has the radiation environment changed, to which the surfaces of, say, the Galilean satellites, have been exposed over time?

Dr. Ray. It depends on what you mean by historically. There have been studies that have looked at the evolution of the field over the last five decades using existing measurements and observations to say that there is a bit of a change. It might be driven by the deep interior, and I think that's the answer to that first question. Anything farther back, say, if you're talking about the dawn of the Solar System, I'm not sure. In terms of how much it would change the moon environment — the moons, at least the ones I care about, are so far embedded within the system that I think you would need quite a big change, almost a turn on, turn off, for it to have any effect.

Mr. Taylor. I'd like to ask a simple dynamical question. This outward transfer of angular momentum through the magnetosphere; ultimately, that's being driven by Jupiter's rotation. Do you have on that basis any estimate for the despinning time of the planet itself?

Dr. Ray. Not off the top of my head, but it is probably a good question for me to do for my third-year students. It's negligible really.

Professor Miller. The answer is that Jupiter is being slowed down, but in order to bring it to a halt will take several times the current age of the Universe.

Dr. Ray. Sorry, yes. I thought he was asking for an exact rate.

Professor Miller. I don't have that on me.

Dr. Quentin Stanley. First of all, the quote you gave at the beginning was Sandro Tacchella.

Dr. Ray. Oh, 'Neither here nor there'?

Dr. Stanley. No, that 'the Universe is a beautiful place'. And the other question is, and this is not to be recommended, if one was floating around in Jupiter, what would the aurora look like?

Dr. Ray. It depends on where you were.

Dr. Stanley. Seeing the footprint of Io, for example.

Dr. Ray. Actually I have another talk for local astronomical societies, where I do this and I put some '*x*'s on the image of Jupiter and say what do you think you'd see? It depends on where you were floating. There are places on Jupiter where, if you were floating, you would be always underneath auroral emission.

But there are also areas where that Io spot would come passing over you every so often and then places where you'd just be bored and disappointed, much like on Earth — in certain equatorial latitudes, where you want to look up, and you are just bored and disappointed. It also will depend on each southern or northern hemisphere because of the different magnetic configurations, and probably the most exciting place to be would be in the polar emission where the aurora is so variable that you really wouldn't know what would happen at any given time.

The President. Would better auroral observations help you much or is it really the spacecraft?

Dr. Ray. The sixteen spacecraft please [laughter].

The President. There's this thing in space called *Webb* that might look.

Dr. Ray. *JWST* is lovely, Olivia. It is absolutely amazing and it's doing great stuff for Jupiter. I think we're going to be very sad when *Hubble* goes, for the amount of information we get.

The President. Thank you very much indeed. May I remind everybody that there is a drinks reception held after this meeting in the RAS Council Room just down the square, and I give notice that the next A&G Open Meeting of the Society will be on Friday, 9th of December 2022.

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Friday 2022 December 9 at $16^{h}\ 00^{m}$
in the Society of Antiquaries Lecture Theatre, Burlington House

MIKE EDMUNDS, *President*
in the Chair

The President. Welcome to you here in the lecture room and also to you in the far-flung corners on-line. This is a hybrid meeting. Questions can be asked at the end of the lecture. As you will be muted can you please use the chat facility to ask your questions which will be read out by Dr. Pam Rowden, a member of the RAS editorial team. On to today's programme. First of all I am very pleased to welcome Dr. Juan Alday, who is the winner of the Keith Runcorn Prize. He is currently postdoctoral researcher at the Open University. He completed his MSc in 2017 at KTH Royal Institute University, Sweden, where he worked on the analysis of *Hubble Space Telescope* observations of Jupiter's moons. He later obtained his PhD from the University of Oxford in 2021 where he worked on the analysis of isotope observations on the *ExoMars Trace Gas Orbiter*. It is a great pleasure to ask you to give your talk. [Applause.]

Dr. Juan Alday. Mars' present-day atmosphere is characterized by a low surface pressure and temperature with traces of water only found in the gaseous and solid phases, namely in the form of water vapour and water ice. Liquid water, an essential ingredient for life as we know it, cannot be sustained at the surface because of the present climatic conditions. On the other hand, numerous geomorphological and mineralogical evidence suggest that liquid water was abundant on Mars earlier in its history, about four billion years ago, carving the surface terrains and producing morphological features that can be observed today through satellite observations.

The atmosphere of early Mars must have been sufficiently warm and dense to enable the presence of liquid water on the surface, which transitioned throughout history to the dry and thin atmosphere we observe today. Enrichment in the heavier isotopes of several species such as H, N, and Ar with respect to Earth suggests that this transition occurred due to the escape of the atmosphere to space. Because of their lower mass, the lighter isotopes of these species escape more easily from the planet, while the remaining atmosphere bound to the planet gets relatively enriched in the heavy isotopes.

Isotopic ratios in atmospheric species not only indicate that atmospheric escape has occurred throughout Martian history, but also, when coupled with evolutionary models, can be used to reconstruct the density and composition of the atmosphere of early Mars. Reconstructing the atmosphere of early Mars from isotope measurements relies on an important parameter known as the escape fractionation factor. This factor determines how quickly the atmosphere gets enriched in the heavy isotopes as escape processes occur or, in other words, determines how much atmosphere must have escaped to space to enrich the relative abundance of the heavy isotopes to their current value.

Estimating the escape fractionation factor requires a rigorous understanding of all atmospheric processes affecting the abundances of the heavy and light isotopes between the lower atmosphere, where most of the atmospheric mass resides, and the upper atmosphere, where escape processes take place. It is in this region between the lower and upper atmosphere that the spectrometers on-board the *ExoMars Trace Gas Orbiter* make their measurements, which we use to understand better the fractionation of the isotopic ratios by several atmospheric processes.

The *ExoMars Trace Gas Orbiter* started science operations in 2018 March and has provided measurements of the vertical structure of the atmosphere of Mars with unprecedented detail. Using measurements from the *Atmospheric Chemistry Suite*, we have measured the O, C, and H isotopic composition in several atmospheric species including H_2O, CO_2, and CO.

When looking at the D/H ratio in water vapour, we have observed that it is about five times higher than that on Earth, consistent with the hypothesis of substantial atmospheric loss throughout history. However, the measured values of the D/H ratio are highly variable. In particular, the measurements reveal that when water vapour condenses into water-ice clouds or onto the polar caps, the D/H ratio gets substantially reduced by a factor of 2–3. This is caused by the different condensation vapour pressures of HDO and H_2O, which favour a preferential condensation of HDO onto ice. Therefore, as condensation occurs, the D/H ratio in the atmosphere gets reduced.

When looking at the $^{13}C/^{12}C$ and $^{18}O/^{16}O$ ratios in CO_2, we have observed a much milder variation. The measurements only suggest variations above an altitude of 100 km above the surface, where the isotopic ratios are found to decrease with increasing altitude. This is produced by the diffusive separation of the isotopes above the homopause: above the homopause altitude, turbulent mixing is not strong enough to mix all isotopes equally, and the density of the heavier isotopes decreases more rapidly with increasing altitude due to their greater mass.

When looking at the $^{13}C/^{12}C$ ratio in CO, we have observed that it is substantially depleted in the heavy isotopes with respect to that in CO_2. These two species are related through photochemical reactions that can affect differently the ^{13}C and ^{12}C isotopes. In particular, solar ultraviolet photons break up CO_2 molecules into CO, but preferentially $^{12}CO_2$ over $^{13}CO_2$. This difference in the reaction rates yields a relative depletion of the $^{13}C/^{12}C$ in CO with respect to that in CO_2.

In conclusion, we observe that several atmospheric processes, including condensation onto ice, atmospheric transport, and photochemistry, can alter the relative abundances of light and heavy isotopes in different species. Understanding these sources of fractionation, and accounting for them in the calculation of the escape fractionation factor, is essential to provide accurate estimates of the composition and density of the atmosphere of early Mars.

The President. Thank you very much. I now invite questions from the floor and on-line, but please identify yourself. Can I ask what was the original composition of the atmosphere of Mars?

Dr. Alday. I think that needs further work. My work has been focussed on measuring these kinds of process. You need to consider evolution, and not only the escape of the atmosphere that can fractionate these isotopes in the long term; there is also outgassing from the surface and perhaps water, instead of escaping into space, ended up in the surface cracks. This is something that we don't know — the effect of different processes producing the isotopes fractionation. Maybe if we knew how they are actually affected we might be able to understand what is going on.

The President. There may be volcanic activity as well.

Dr. Alday. Yes.

The President. Was it like the early-Earth's atmosphere?

Dr. Alday. From what I have read — some papers say that CO_2 was very abundant on Mars; others say that the atmosphere may have been nitrogen-based.

The President. We'll just have to get you back in a few years to tell us. Are there any questions from the floor?

Mr. Christopher Taylor. You said that deuterium on Mars was about five times more abundant than on the Earth, and attributed that to the escape fractionation factor.

The President. I think that these were ratios relative to the Earth.

Mr. Taylor. The ratio of deuterium relative to H is five times more abundant on Mars than on the Earth. I thought that the ratio in the atmosphere of Jupiter was about five times what it is on Earth, so surely there is no chance of escape fractionation because the escape velocity of Jupiter is so much higher?

Dr. Alday. What was the original fraction of D to H when Mars was formed? It is assumed that the primordial D/H ratio is similar to that of Earth but that on Jupiter was not necessarily similar to that on Mars and Earth. You use isotopic measurements in Martian meteorites typically with respect to the Earth; this gives you a baseline, but typically for the amount of atmosphere and the amount of H_2O that has been lost, you look at the past isotopic ratio from Martian meteorites and the current isotopic ratio in the atmosphere, in order to make this estimation.

Dr. Paul Wheat. As I understand it, I don't think that there is a magnetic field on Mars, therefore the incoming solar radiation and the particles are much more severe, including the ultraviolet, than they are on Earth. How much does that affect the atmospheric chemistry?

Dr. Alday. Not having a magnetic field? I'm not sure; that is the short answer. Actually it is not really known when Mars lost its magnetic field or why, but that definitely affects the escape rates because the magnetic field is not shielding the planet, and the particles from the Sun actually increase the escape rates, and the chemical interactions between the charged particles and the atmosphere; but I'm not really sure how it changes the chemistry.

The President. Thank you very much indeed. The next speaker is Dr. Rebecca Smethurst who won the Winton 'A' award for research by a postdoctoral researcher in astronomy. Rebecca is a Royal Astronomical Society Research Fellow in the University of Oxford. Her work specializes in the growth of supermassive black holes and the effect of AGN feedback that results from that growth. She is part of the SDSS and the Galaxy Zoo collaboration. Her career has shown the most promising development and she has also done a lot of work in the field of public understanding and is well-known for her *You Tube* channel, I believe.

Dr. Rebecca Smethurst. Today I am going to talk about the growth of supermassive black holes (SMBHs). There has to be a process to move material from a stable orbit into the SMBH by the transfer of angular momentum. There are a few processes that can do that, not least the merging of two galaxies, but today I want to try and convince you that this is done by an internal process. If you plot galaxy bulge mass against SMBH mass there does appear to be a correlation. If you merge two galaxies of similar mass and little gas content then you will end up with a galaxy which is all bulge, *i.e.*, an elliptical galaxy. If one galaxy is much smaller than the other then you will build a bulge in the centre of the existing stellar disc in that process and also funnel stellar material to the centre to grow the black hole. The galaxy and black hole grow together, something known as co-evolution. We think that this co-evolution must be regulated by a process which stops galaxies getting too large. This comes from the observed luminosity function for galaxies which is formed by doing a count of the distribution of brightness for many galaxies. Comparing the luminosity function to the accepted ΛCDM model of some 20 years ago, then they did not match. The simulations were missing a process which is called AGN feedback where an accreting SMBH is feeding energy back into the galaxy through an outflow, wind, or jet. If we add that process, at least at the high-mass end of galaxies, then we find that the observed properties begin to match our simulations. At the low-mass end there is a similar process with supernova feedback blowing back into the galaxy. However, there is a huge disconnect between theory and observers such as myself. We have found this happens over a large range of galaxies. The best evidence is the correlation between the mass of the BH and the mass of the galaxy which says that if you grow one then you grow the other, but then if something stops growing the BH, like AGN feedback, then you have this correlation. There have been a few results that challenge this paradigm of galaxy mergers causing co-evolution and regulating this growth through feedback.

In 2013, for galaxies observed at $z = 2$, which is the peak epoch for star formation, it was found that only 27% of star formation was triggered by galaxy mergers, suggesting that the BH growth is not powered by galaxy mergers. In 2017, Pontzen *et al.* modelled the merger of two galaxies with AGN feedback and discussed what happened to the star-formation rate after the merger. They found that if the BH accretion switched off after the merger then the galaxy begins forming stars again. Then in the Millennium simulation, in a paper by Parry, Eke and Frenk in 2021, they find that bulge growth is not dominated by mergers until you get above 10^{11} solar masses — below that mass the process is dominated by disc instabilities.

How do we test whether BHs can grow in the absence of mergers? We looked at a spiral galaxy without a bulge — it is completely disc-dominated. The centre is a very bright point — the BH is accreting gas and lighting up for us to see. Further examples of this galaxy type are difficult to find — they have been left alone for the last 11 billion years of their evolution. Add to that the fact that only

10% of the galaxies have AGN.

We picked 101 galaxies from the SDSS. They are mostly disc-dominated but they do have very bright centres. The bright nuclei appear almost purplish compared with the blue and yellow light of the surrounding galaxy. These are AGN that are accreting mass rapidly. We used an *HST* survey to confirm that there was a bulge hidden behind the AGN. Once we had spectra we looked at the H-alpha emission from the BH accretion disc and the breadth of the line gave an estimate of the SMBH mass. Some of the BHs in this sample have grown to 10^9 solar masses — as large as those which might be found in elliptical galaxies. This is a surprise and clearly indicates that there is another process which is not down to galaxy mergers. We also worked with the Horizon–AGN team to see if they picked out galaxies which had not had a merger, did they find a similar result? They see BH and galaxy growth without mergers so there is clear evidence for co-evolution in the absence of mergers.

Using the Horizon–AGN simulation code we projected backwards to see where the mass came from and to look at the cumulative growth of BHs over the history of the Universe, work led by Gareth Martin. At $z = 0$, 35% of the mass of SMBHs are down to galaxy mergers and the rest is something else. Combining their simulations with observations we have a new way of looking at BH and galaxy co-evolution and the non-merger mechanism is dominating the long epochs between galaxy mergers, so it appears that co-evolution is dominated by non-merger processes.

We observed the four brightest bulgeless galaxies with AGN using *Keck Cosmic Web Imager* (*KCWI*) on Mauna Kea. Each pixel is a spectrum and shows the broad hallmarks of AGN — a broad pink emission line representing the accretion disc whilst a blue-shifted line indicates an outflow from the AGN, *i.e.*, moving in a different direction to the gas in the accretion disc, and red emission indicates star formation. It is very exciting to see merger-free outflows which are powering AGN feedback, so could these outflows stop star formation in these galaxies? We found the outflow velocities up to 1700 km s^{-1} and then looked at the escape velocity at the greatest extent of the outflow. The outflow velocity was, on average, thirty times larger than the escape velocity of the galaxy. It suggests that the outflow could be expelling gas which could lead to future star formation, stopping the galaxy from getting too large and regulating the growth of the central BH. We do not know what causes the outflow, but if we can determine the outflow rate and the rate at which the BH is accreting then we can work out a lower limit on the amount of gas being funnelled into the centre. The rate of inflow is between 0·18 and 0·77 solar masses yr^{-1}. Compared to the typical outflows in the local Universe this appears to be normal, which is strange as the galaxies have been chosen to be not normal. We found that non-merger processes can easily fuel the growth of SMBHs and power AGN outflows.

We also checked the spin-axis of the galaxy and the BH spin — are they aligned or not? This can determine how much effect the feedback can have on the galaxy as well. In merger-free BHs we found they were much more likely to be aligned than not. We would like to test this with *HST* in the future to determine if the axes aligned with the galaxy discs because they are coming from a spinning BH. There is future work to be done using *MUSE* on the *VLT* to determine the impact on the outflows.

The President. Thanks very much. Questions, please?

Dr. Hannah Dalgliesh. From the sample of 101 galaxies, they appear very much face-on. Would that introduce any biasses at all?

Dr. Smethurst. The reason that they are face-on is because I selected them first from X-ray studies. I would love to get a sample which is inclination-bias free. It is not something that we have looked at necessarily. We do have a range of inclinations.

Reverend Garth Barber. Could you say something about the very-high-*z* supermassive black holes?

Dr. Smethurst. This is a huge problem — how do you get supermassive so soon? In simulations they rely on a much larger seed BH mass being formed in SN — starting at 10^4 solar masses and increasing from there. What is interesting to think about is whether this merger-free accretion could actually help with that problem. Merger-free accretion could be more efficient because you end up with a higher spin in the BH accretion disc which would decrease as well. It might also result in a decrease in luminosity and that might mean they are more efficient. We are looking into that in terms of ratios of outflow rates in the disc-dominated galaxies and in mergers as well. I think you can solve that with simulations if you had higher resolution and a larger cosmological volume. These two things don't always go together unfortunately.

The President. Anything on-line yet? Come on on-liners — ask your questions.

Dr. Zbigniew Kolendowicz. Thank you for a very interesting talk. You have given me lots of ideas already. It's coming up to Christmas, so in 5 GYr's time it won't matter to us as the Earth will not be here. In 5 GYr a large galaxy, Andromeda, will collide with the Milky Way and form what you could call the Milky Andromeda Galaxy. My question is: will it become an elliptical galaxy, or will it be too big, and will there be a merger of the BHs or will the two rotate around each other and produce an AGN of some sort?

Dr. Smethurst. It would be classed as a minor merger because Andromeda is so much larger than the Milky Way. The SMBHs would merge in the centre — simulations indicate that it would probably take a couple of GYr for this to happen and that would lead to some accretion. I don't think it would form an elliptical galaxy — more likely it would form a geometric bulge in the centre with a surrounding disc. The Milky Way black hole is much smaller than it should be; the fact that we haven't got a superactive BH could be the reason that we are here. There has been no outflow or jets from the Galactic Centre over the four billion years during which the Earth was evolving. The Milky Way doesn't actually have a formal bulge, it is more like a disc.

Dr. Pamela Rowden. A question from Aadil Desai. "Can it be taken for granted that all galaxies have black holes at their centres?"

Dr. Smethurst. That is the assumption, yes, although there have been claims that a couple of dwarf galaxies do not. That leads to the question, does the galaxy form first or does the BH form first in the early Universe? We still don't know.

The President. I think we should move on to the next talk. It is fascinating to think that we will be sending happy-merger cards rather than happy-Christmas cards in 5 GYr's time. The next talk is our Diary talk for this year. We normally have one major talk per year on the history of astronomy at the Ordinary Meetings. Today's talk is entitled 'Herschel 2022: a double anniversary', and it will be given by Dr. Patricia Fara who is an Emeritus Fellow of Clare College Cambridge where she was Senior Tutor for ten years. She originally read physics at Oxford but is now in the Department of History and Philosophy of Science at Cambridge. In addition to her academic teaching she has written many popular books and articles and was awarded the 2022 Abraham Pais Prize by the American Physical Society.

Dr. Patricia Fara. The year 2022 marks an important anniversary for the

Royal Astronomical Society — 200 years since the death of its first President, William Herschel. But 2022 is also exactly 250 years since his sister Caroline joined him in England to study music. Neither of them could have foreseen that she would not only discover several comets but also play a crucial role as his collaborator in the research projects that made him world-famous. Caroline was well-known at the time, and her importance was recognized formally by King George III, who granted her a scientific salary, and also by the Society, who paid her the tribute of a gold medal.

The history of science is often simplistically told as a succession of great male geniuses, and Caroline has been eclipsed by William's reputation. While he does, of course, deserve to be celebrated as a superb path-breaking astronomer, William's multiple achievements would have been impossible without Caroline. As Vice-President James South put it admiringly, "Who participated in his toils? Who braved with him the inclemency of the weather? Who shared his privations? A female — who was she? His sister."

Astronomy depends on teamwork, and the siblings established a family enterprise with many employees. On one occasion, when William asked Caroline to adjust a telescope, she reported "having to run in the dark on ground covered foot deep with melting snow, I fell on one of these hooks which entered my right leg about 6 inches above the knee, my brothers call make haste I could only answer by a pitiful cry I'm hooked".

Caroline also organized much of the construction work for their giant 40-foot telescope at Slough. A "perfect Chaos of business", she wrote, as she tried to coordinate around 40 workmen, each identified by a numbered shirt, who spent three months preparing the site before the bricklayers, local carpenters, and ironmongers arrived. Using this large telescope was a double act. While William perched at the upper end, Caroline spent her nights in a little hut on the ground connected to him by a speaking tube; she recorded his observations and later carried out the calculations needed to compile star catalogues.

They were both born in Hanover, where William and his father were military musicians. In 1757, William evaded political complications by taking refuge in England, then ruled by the Hanoverian Georges. A skilled instrumentalist and composer, William eventually settled in the fashionable spa town of Bath with three of his brothers. Tempted by promises of a singing career, Caroline joined them in 1772, and performed successfully several times. But after William developed a passion for astronomy, she was obliged to abandon music and work with him at home. Their comfortable house survives as a museum that is packed upstairs with astronomical and musical instruments, yet still retains the earth-floored basement where Caroline spent long hours sieving horse manure to make smooth beds for metal mirrors.

As their reputation grew, they moved nearer London and continued their initiative of building telescopes on an unprecedentedly large scale. In addition to running the household, Caroline's tasks included carrying out mathematical calculations, observing throughout the night, recording data, compiling star catalogues, and keeping records of distinguished visitors. For example, when their 40-foot tube still lay on the ground, she encouraged admirers to walk through it: "Come, my Lord Bishop, said King George; I will show you the way to Heaven."

Their massive instruments enabled them to peer far out into space beyond the Solar System. William remarked that the heavens "resemble a luxuriant garden, which contains the great variety of productions in different flourishing beds": like botany, astronomy entailed collecting and classifying, and was regarded as a suitable topic for women. Together the Herschels examined many different types of nebulae and double stars, while Caroline came to specialize in detecting new comets with her own small sweeper telescope. When William first spotted what is now known as the planet Uranus, he tracked it for several weeks believing it to be a comet, but her identifications proved more accurate. Starting in 1786, Caroline discovered eight new comets, thus substantially boosting the previous known number of around thirty. Her personal notebooks are preserved in the Society's archive, and they include drawings and descriptions such as this: "I have calculated 100 nebulae today, and this evening I saw an object which I believe will prove tomorrow night to be a Comet."

Caroline's fame spread internationally after she wrote to the Secretary of the Royal Society, timidly beginning "I venture to trouble you with the following imperfect account of a Comet". Three weeks later she was summoned to Windsor Castle so that George III could see it for himself. One of the royal attendants, the novelist Fanny Burney, abandoned her game of cards to rush into the garden and climb up the steps of the telescope that had been temporarily installed, declaring "It is the first lady's comet, and I was very desirous to see it".

Caroline grew increasingly embittered after her brother got married, and later went back to Germany, although she remained in frequent contact with William's son John Herschel. Unfortunately, she contributed to being written out of history by repeatedly making self-deprecatory remarks: "I am nothing, I have done nothing", she wrote, "a well-trained puppy-dog would have done as much". Yet occasionally she revealed a sharper, wittier aspect of her character. After meekly thanking the Astronomer Royal for having "flattered her vanity" by printing her star catalogue, she began demeaning herself: "You see, sir, I do owe myself to be vain, because I would not wish to be singular; and should be ever a woman without vanity?" But then came the sting in the tail: "Or a man either — only with this difference, that among gentlemen the commodity is generally styled ambition."

The President. Thank you very much for your introduction to these amazing people. How many of you have been to the Herschel Museum? How many have not been? I trust you are planning your summer holidays and you will do so. The RAS has an interest there and we regularly collaborate with exhibitions *via* our Librarian. If you are ever in Bath, I thoroughly recommend you to visit the Herschel Museum.

Dr. Rowden. A question from Aadil Desai. "Would you say that Isaac Newton was not scientific, as he connected seven colours with seven musical notes and later on Herschel discovered infrared light."

Dr. Fara. What I would say is that he is not a scientist because the word 'scientist' was not invented until 1833. The other reason we might not call him a scientific man is that he was a very deep believer in God. In the second edition of the *Principia* written in 1713 he emphasizes that God was central to everything. There are many ways in which by some criteria he is not scientific. On the other hand it is a bit difficult to exclude him from the whole of science. It depends when you think science began: what constitutes science is constantly changing. What Newton did seemed reasonable at the time — it conformed with the existing rules of knowledge but it's not what we think now.

Dr. Rowden. There is a question from Andrew Thomas. "Was a singing career realistic and are there any reviews of the Bath concerts?"

Dr. Fara. I think it was very realistic. Bath was an excellent place to undertake that sort of work. It is said that she wrote music herself — unfortunately none of it survives, but quite a lot of William's music does survive. Perhaps the Royal

Society and the RAS could collaborate to produce a William Herschel concert?

The President. Well, actually, we have already done that. It was part of the Herschel celebrations in Bath and there was also a concert in York, and you can buy CDs of William's music.

Dr. Rowden. I have a question from Charles Draper. "Thanks for the talk. Caroline is better recognized today for being a great inspiration for many. We now have two astronomical prizes in her name — what else should be done?"

Dr. Fara. I believe there is a crater on the Moon named for her. We just saw one of the Mars explorers named for Rosalind Franklin, so perhaps a spacecraft could be named after her.

Dr. Robert Massey. There is also an art installation made by our former artist-in-residence who created a fantastic image of stars to which Caroline contributed. I'm pretty sure that she is going to set it up at Jodrell Bank.

Dr. Fara. I should also add that the RAS archivist and I collaborated to produce a podcast on her birthday.

Mrs. Ahlam Abdi. During that time were there any other ladies who were astronomers?

Dr. Fara. In the period before the Herschels the most famous person in England was the wife of John Flamsteed who also collaborated with him in his observations. After he died, she was responsible for publishing his star catalogue. Also, in Germany, there were lots of astronomical women — astronomy was a craft and it was practised at home. I think it was the Frenchman Lalande who, in the 18th Century, compiled a book about female astronomers. There were some in France and England and there were also the women called computers who were carrying out all the calculations. Rather than trying to find the equivalent of Isaac Newton, we should recognize that women could not go to university and they did lead very resticted lives. On the other hand science was practised at home which inevitably meant that a lot of women became involved and they were important for translation, compiling notes, looking after collections, running museums, teaching, and all of the things that were absolutely vital if science was going to spread. When Newton published *Principia* he wasn't the slightest bit interested in communicating his ideas. The book was in Latin so only scholars could understand it and he said that he deliberately wrote very complicated maths because he didn't want to be bothered by "little smatterers in mathematics." His theory became widespread thanks to a lot of work by men and women who translated and interpreted his words for school or university textbooks and devised experiments which explained his ideas. If you consider the spread of science in that sort of way then women play a more prominent role than we had ever realized. One of the best examples is a contemporary of Caroline Herschel, Marie-Anne Paulze, who was married to the great French chemist Lavoisier. There is a collection of her drawings in an American university. They show her in the laboratory recording experiments. They married when she was 13 and one of the first things she did was to learn English so that they could communicate with people like Joseph Priestley. She was central to Lavoisier's research and she did all the diagrams in his big book on chemistry, but gets no credit for it.

The President. Perhaps that is the note on which to conclude. Thank you very much. May I remind you of the drinks reception in the Council Room and I give notice that the next Ordinary A and G meeting will be on Friday the 13th of January, 2023. In the meantime I wish you all a happy Christmas and a prosperous New Year.

REDISCUSSION OF ECLIPSING BINARIES. PAPER 14: THE F-TYPE SYSTEM V570 PERSEI

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V570 Per is a binary star system containing two F-type stars in a 1·90-d period circular orbit. It shows shallow partial eclipses that were discovered from its *Hipparcos* light-curve. We present an analysis of this system based on two sectors of high-quality photometry from the NASA *Transiting Exoplanet Survey Satellite* (*TESS*) mission, and published spectroscopic light ratio and radial-velocity measurements. We find masses of 1·449 ± 0·006 and 1·350 ± 0·006 $M_{\odot}$, and radii of 1·538 ± 0·035 and 1·349 ± 0·032 $R_{\odot}$. The radius measurements are set by the spectroscopic light ratio and could be improved by obtaining a more precise light ratio. The eclipses in the *TESS* data arrived 660 ± 30 s later than expected, suggesting the presence of a faint third body on a wider orbit around the eclipsing system. Small trends in the residuals of the fit to the *TESS* light-curve are attributed to weak starspots. The distance to the system is close to the *Gaia* DR3 value, but the *Gaia* spectroscopic orbit is in moderate disagreement with the results from the published ground-based data.

Introduction

Detached eclipsing binary stars (dEBs) are our main source of measurements of the physical properties of normal stars. The number of dEBs for which precise measurements are available is increasing gradually, as traced by reviews of this subject[1–3] as well as compiled catalogues[4–6]. The *Detached Eclipsing Binary Catalogue*★ (*DEBCat.*, ref. 6) currently lists just over 300 dEBs for which masses and radii are measured to 2% precision or better, helped by the widespread availability of light-curves from space telescopes[7].

dEBs are useful in understanding the physical processes that govern the structure and evolution of stars. They have been used to calibrate the amount of convective-core overshooting[8–10] albeit with conflicting results[11], the size of the convective core in massive stars[12], mixing length[13], and the radii of low-mass stars[14,15]. They are also sources of distance measurements which have been used to calibrate the cosmological distance scale[16,17].

We are currently pursuing a project to increase the number of dEBs with reliable measurements of their masses and radii[18], primarily using new observations from the NASA *Transiting Exoplanet Survey Satellite* (*TESS*) mission[19]. *TESS* has observed thousands of dEBs[20–22], many of which have available high-quality radial-velocity (RV) measurements. In this context, we present an analysis of the V570 Persei system.

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

V570 Per (Table I) is an F-type dEB which was discovered using data from the *Hipparcos* satellite[23] and given its variable-star name by Kazarovets *et al.*[24]. It was selected for analysis by Munari *et al.*[25] in the context of assessing the expected performance of the *Gaia* satellite in the study of dEBs. These authors used the *Hipparcos* photometry of V570 Per along with ground-based spectroscopy restricted to the 850–875-nm wavelength range to mimic the expected characteristics of the *Gaia* observations. They measured the masses of the components of V570 Per to 2·5%, and the radii to low precisions of 10% and 25% due to the large scatter in the *Hipparcos* data and the shallow eclipses shown by this dEB. Tomasella *et al.*[26] (hereafter T08) presented a more detailed study of V570 Per based on new ground-based photometry, and the same spectroscopy, but this time using the full available 450–948-nm wavelength range. They constrained the model of the light-curve using spectroscopically-measured light contributions of the two stars in the *V* band. They determined the atmospheric parameters of the component stars *via* a χ^2 fit of synthetic spectra to their observed spectra, a method which neglected the systematic errors inherent in this process.

TABLE I

Basic information on V570 Per.

Property	*Value*	*Reference*
Right ascension (J2000)	$03^h09^m34^s{\cdot}94$	27
Declination (J2000)	$+48^{\circ}38'28''{\cdot}7$	27
Henry Draper designation	HD 19457	28
Hipparcos designation	HIP 1673	29
Gaia DR3 designation	435997252803241856	27
Gaia DR3 parallax	8·2952 ± 0·0355 mas	27
TESS Input Catalog designation	TIC 116991977	30
B magnitude	8·55 ± 0·02	31
V magnitude	8·09 ± 0·01	31
J magnitude	7·160 ± 0·026	32
H magnitude	6·948 ± 0·017	32
K_s magnitude	6·882 ± 0·020	32
Spectral type	F3 V + F5 V	26

Observational material

The *TESS* mission[19] observed V570 Per in sectors 18 (2019/11/02 to 2019/11/27) and 58 (2022/10/29 to 2022/11/26), in both cases in short-cadence mode with a 120-s sampling rate. We used the LIGHTKURVE package[33] to download these data and reject points flagged as bad. The simple aperture photometry (SAP) and pre-search data conditioning SAP (PDCSAP) data[34] are almost indistinguishable, so we used the SAP data in our analysis for consistency with previous papers in this series.

We converted the data to differential magnitude and subtracted the median magnitude for further analysis, ending up with 15256 data points from sector 18 and 19475 from sector 58. On further inspection we found that the first stretches of data from both halves of the sector 18 light-curve were affected by instrumental systematics, so we trimmed them by removing data in the intervals [2458790·6,2458792·5] and [2458801·0,2458804·7]. This left a total of 32719 data points over both *TESS* sectors (Fig. 1).

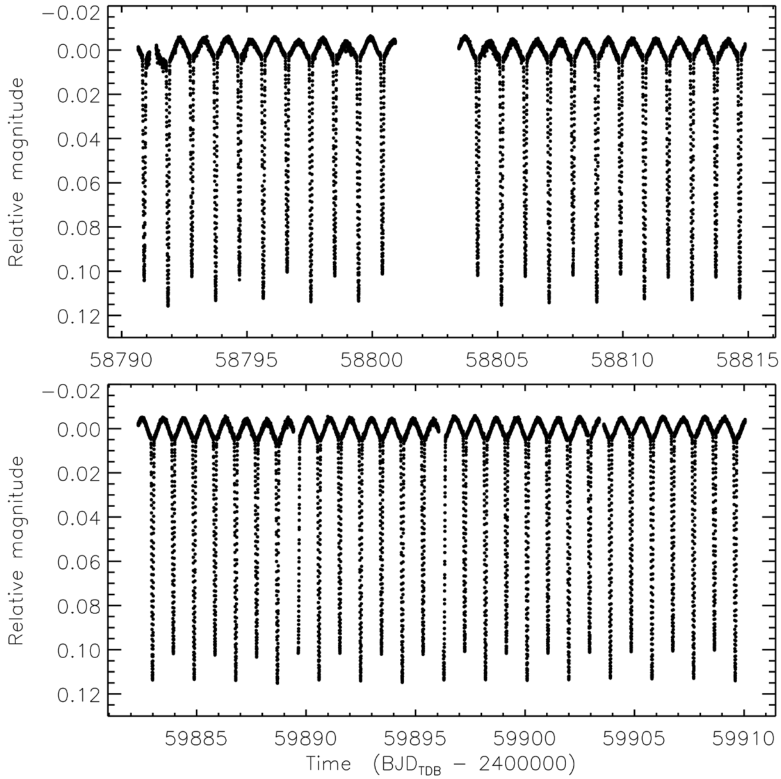

Fig. 1

TESS short-cadence SAP photometry of V570 Per from sectors 18 (top) and 58 (bottom). The flux measurements have been converted to magnitude units then rectified to zero magnitude by subtraction of the median.

We queried the *Gaia* DR3 database* for objects within 2 arcmin of V570 Per. A total of 108 were found, all of which are fainter than V570 Per by at least 7·2 mag in the *Gaia G* band. We deduce that the amount of light contaminating the *TESS* aperture for this dEB is negligible.

Light-curve analysis

We modelled the light-curves from the two sectors both individually and together, using version 43 of the JKTEBOP† code[35,36]. In all cases the parameters of the fit included the fractional radii of the stars (r_A and r_B), expressed as their sum ($r_A + r_B$) and ratio ($k = r_B/r_A$), the orbital inclination (i), the central surface-brightness ratio ($\mathcal{J}$), the ephemeris (period P and reference time of primary minimum T_0), and the coefficients of the reflection effect. We define star A to be the one eclipsed at the deeper minimum and star B to be its companion. A circular orbit was assumed based on the appearance of the light-curve and of the RVs presented by T08 — when allowing for an eccentric orbit we found

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

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

a best-fitting eccentricity of e = 0·0053 and almost no change in the other parameters. We included a quadratic function *versus* time for each half-sector to account for slow changes in the brightness of the dEB due to instrumental effects.

The eclipses are partial and shallow, so the light-curve solution suffers from a strong degeneracy between k, i, and J (*e.g.*, refs. 37 and 38). This effect was found by T08 when modelling their ground-based photometry, and remains present in the much more extensive and higher-precision *TESS* data used in the current study. We therefore applied a spectroscopic light ratio as a constraint, in the same way as done in our work on V1022 Cas[39] and HD 23642[40]. The light contributions found by T08 correspond to a light ratio of ℓ_B/ℓ_A = 0·667 ± 0·053 in the V band. We propagated this to the *TESS* passband using the response function from Ricker *et al.*[19], theoretical spectra from Allard *et al.*[41], and the effective temperature ($T_{\rm eff}$) values from T08, finding ℓ_B/ℓ_A = 0·703 ± 0·057.

Limb darkening (LD) was included in the fit[42] using the power-2 law[43] and theoretical LD coefficients[44]. Fitting for the scaling coefficient ("c" in the terminology of Maxted[45]) for both stars yielded determinate values and little change in the other parameters, so was adopted as the default approach.

The amount of third light (L_3) has a significant effect on the best-fitting parameter values. If fitted, it converges to a formally significant but unphysically negative value (–0·083 ± 0·018) despite the negligible amount of light from nearby stars (see previous section). We therefore fixed it at zero in our default solution, but added contributions to the error bars based on the change in parameter values by assuming L_3 = 2% instead. For information, such an assumption decreases r_A by 1·1% and increases r_B by 0·4%.

The best fits to the light-curves from the two sectors are shown in Figs. 2 and 3. These plots show the result of a fit to both sectors simultaneously, but divided into individual sectors in the plots. Slow trends in the residuals are apparent in both cases, and are discussed below.

The fitted parameters are given in Table II. Uncertainties in the parameters were determined using Monte Carlo and residual-permutation simulations[46,47].

TABLE II

Adopted parameters of V570 Per measured from the TESS light-curves using the JKTEBOP code. The uncertainties are 1σ and were determined using Monte Carlo and residual-permutation simulations.

Parameter	*Value*
Fitted parameters:	
Time of primary eclipse (BJD_{TDB})	2459894·392999 ± 0·000009
Orbital period (d)	1·90093830 ± 0·00000002
Orbital inclination (°)	77·294 ± 0·048
Sum of the fractional radii	0·31715 ± 0·00057
Ratio of the radii	0·877 ± 0·036
Central-surface-brightness ratio	0·8767 ± 0·0033
LD coefficient c for star A	0·548 ± 0·017
LD coefficient c for star B	0·516 ± 0·020
LD coefficient α for star A	0·498 (fixed)
LD coefficient α for star B	0·467 (fixed)
Orbital eccentricity	0·0 (fixed)
Derived parameters:	
Fractional radius of star A	0·1690 ± 0·0028
Fractional radius of star B	0·1482 ± 0·0035
Light ratio ℓ_B/ℓ_A	0·683 ± 0·060

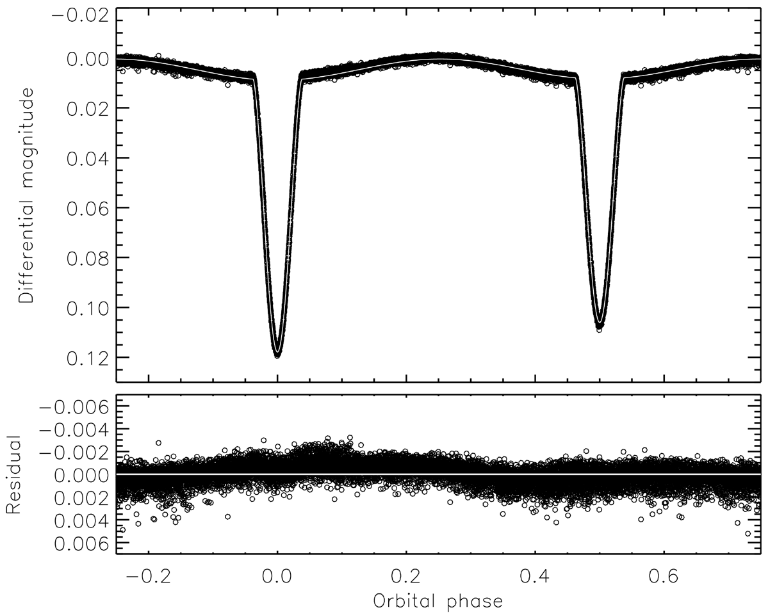

FIG. 2

Best fit to the *TESS* sector-18 light-curve of V570 Per using JKTEBOP as a function of orbital phase. The residuals are shown on an enlarged scale in the lower panel.

The Monte Carlo error bars are significantly larger than the residual-permutation alternatives because the latter do not account for the uncertainty in the spectroscopic light ratio. We therefore adopted the Monte Carlo error bars for all parameters. The dominant source of uncertainty is the spectroscopic light ratio, which could be improved by further observations and analysis.

The out-of-eclipse variability

The best fits to the light-curves (Figs. 2 and 3) show slow trends in the residuals which differ between the two sectors. Our preferred interpretation of this is small brightness variations present on the surface of one or both stars, with the star(s) rotating synchronously with the orbit in order to obtain the consistent phasing in Figs. 2 and 3. This could be caused by starspots, and evolution of the spot configuration is a natural explanation for the differences between the residuals of the fits to the two sectors. The $T_{\rm eff}$ values of the stars are relatively high for this explanation, but are only slightly higher than KIC 5359678 for which spot activity was clearly detected[48,49]. The lack of increased residuals during eclipse suggests the spots are either a similar temperature to the rest of the photosphere and/or are located on parts of the star(s) that are not eclipsed.

We checked for the possibility of pulsations by calculating a periodogram of the residuals of the fit to the data from sector 58, using the PERIOD04 code[50]. Significant signals were found at the orbital period and half the orbital period, in agreement with the starspot hypothesis. No evidence for either δ Scuti or γ Doradus pulsations were found, despite a significant number of such pulsators now being known in dEBs[51–55].

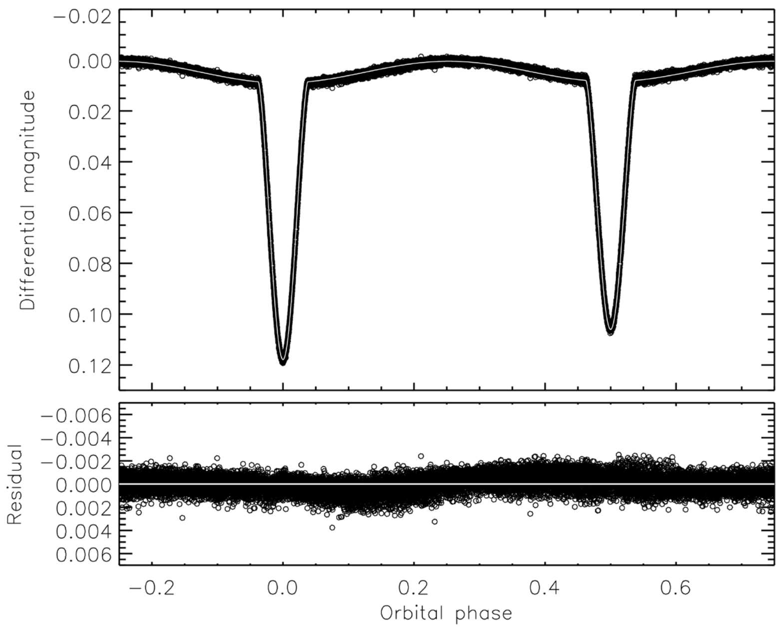

FIG. 3

Best fit to the *TESS* sector-58 light-curve of V570 Per using JKTEBOP as a function of orbital phase. The residuals are shown on an enlarged scale in the lower panel.

Radial velocities

T08 measured RVs of both stars from each of 31 high-quality échelle spectra obtained using the Asiago 1·8-m telescope. We obtained these from Table 2 in T08 and modelled them using JKTEBOP, adopting a circular orbit and separate systemic velocities (V_γ) for the two stars. We fitted for velocity amplitudes (K_A and K_B), $V_{\gamma,A}$, $V_{\gamma,B}$, and T_0. The period was fixed at the value from Table II. Uncertainties were calculated from 1000 Monte Carlo simulations[35,56] after adjusting the sizes of the error bars to give a reduced χ^2 of unity for the RVs for each star.

We found K_A = 113·94 ± 0·24 km s^{-1}, K_B = 122·33 ± 0·22 km s^{-1}, $V_{\gamma,A}$ = 23·15 ± 0·16 km s^{-1} and $V_{\gamma,B}$ = 23·09 ± 0·14 km s^{-1}, where the uncertainties in the systemic velocities do not include any transformation onto a standard system. The best fits are shown in Fig. 4. We cannot compare the K_A and K_B values directly with the results from T08 because they did not calculate those parameters explicitly.

We found an offset of 658 ± 29 s between the T_0 from the RV fit and that predicted from the ephemeris in Table II. Further investigation suggests that this offset is also present in the times of minimum light given by T08 and Hubscher *et al.*[57]. As the current work is the first by the author that used the LIGHTKURVE package to access *TESS* data, one possibility is that this approach has caused an offset in the time stamps. We checked this by using LIGHTKURVE to download *TESS* light-curves for ZZ UMa and ZZ Boo and compared them to

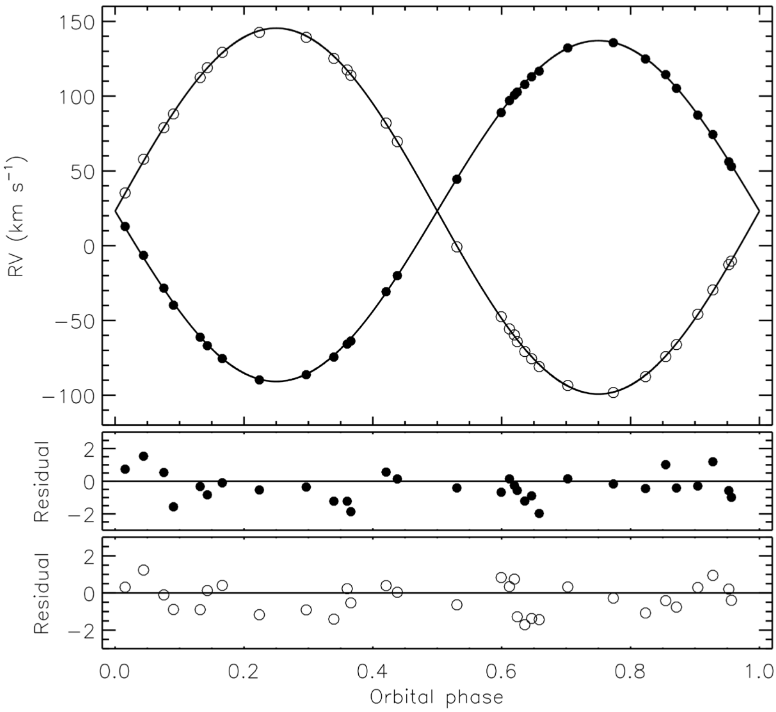

FIG. 4

RVs of V570 Per from T08 (filled circles for star A and open circles for star B) compared to the best-fitting spectroscopic orbits from our own analysis using JKTEBOP (solid curves). The residuals are given in the lower panels separately for the two components.

those used in refs. 58 and 59. No offset in the timings was found, suggesting that the timing offset is an astrophysical effect, perhaps caused by a third component on a wider orbit around V570 Per.

V570 Per is present in the *Gaia* DR3 catalogue *Non-single-star orbital models for sources compatible with Double Lined Spectroscopic binary model** which reports objects detected as double-lined and with a fitted spectroscopic orbit[60,61]. The orbital parameters given are $e = 0{\cdot}0029 \pm 0{\cdot}0019$, $K_1 = 123{\cdot}86 \pm 0{\cdot}28$ km s^{-1}, and $K_2 = 113{\cdot}82 \pm 0{\cdot}24$ km s^{-1}, based on RVs from 24 spectra. The eccentricity is very small and consistent with zero, as expected. We find that K_2 is in good agreement with our K_A, but that K_1 is moderately discrepant with our K_B. It is clear that the identities of the stars have been swapped, but the source of the K_1/K_B discrepancy is unknown. We chose not to use these results because the spectra and RVs on which they are based are not publicly available so cannot be checked. It is relevant that Tokovinin[62] has found issues with the *Gaia* DR3 K_1 and K_2 values in the sense that a significant fraction (14 of 22 in that case) have underestimated values or other problems.

*https://vizier.cds.unistra.fr/viz-bin/VizieR-3?-source=I/357/tbosb2

Physical properties of V570 Per

We determined the physical properties of V570 Per using the JKTABSDIM code[63]. The input values to this were: the r_A, r_B, i, and P from Table II; the K_A and K_B from the RV analysis; the T_{eff} values from T08 with the error bars increased to ±50 K to account for the systematic uncertainties of the T_{eff} scale for F-stars[64–66]; an interstellar reddening of $E(B-V) = 0·05 \pm 0·02$ mag from the STILISM* on-line tool[67,68]; the B and V magnitudes from *Tycho*-2[31] which are averages of 12 measurements at effectively random orbital phases; and the JHK_s magnitudes from 2MASS[32] converted to the Johnson system using the transformations from Carpenter[69]. The 2MASS magnitudes were taken at phase 0·10 so are representative of the average brightness of the system. The results are given in Table III, where the error bars have been propagated individually from each input parameter.

The agreement between the measurements in Table III and the results from T08 is good, with all quantities within 1σ. The radii of the stars have been determined to 2·3% precision, which is slightly worse than managed by T08 despite the availability of much better photometry for the current study. This arises because the precision of the radius measurements is limited by the spectroscopic light ratio applied in the photometric analysis, and perhaps from underestimated error bars in T08. A better spectroscopic light ratio is needed to measure the radii more precisely.

The synchronous rotational velocities are consistent with the $v \sin i$ values measured by T08. This is in agreement with our assertion that the trends in the residuals of the fit to the light-curves are due to starspots rotating synchronously with the orbit.

Inversion of the *Gaia* DR3 parallax gives a distance to the system of d = 120·55 ± 0·52 pc, which is 1·4σ longer than that found in our own work *via* the K-band surface brightness method[63] and calibrations from Kervella *et al.*[71]. An increase in $E(B-V)$ to 0·1 mag would bring our optical (BV) and infrared (JHK_s) distances into better agreement at the expense of shortening the distance

TABLE III

Physical properties of V570 Per defined using the nominal solar units given by IAU 2015 Resolution B3 (ref. 70).

Parameter	*Star A*	*Star B*
Mass ratio M_B/M_A	0·9314 ± 0·0026	
Semi-major axis of relative orbit ($R^N_\odot$)	9·100 ± 0·013	
Mass ($M^N_\odot$)	1·4489 ± 0·0063	1·3495 ± 0·0062
Radius ($R^N_\odot$)	1·538 ± 0·035	1·349 ± 0·032
Surface gravity (log[cgs])	4·225 ± 0·020	4·308 ± 0·021
Density ($\rho_\odot$)	0·398 ± 0·027	0·550 ± 0·039
Synchronous rotational velocity (km s^{-1})	40·93 ± 0·92	35·89 ± 0·85
Effective temperature (K)	6842 ± 50	6562 ± 50
Luminosity log($L/L^N_\odot$)	0·669 ± 0·023	0·483 ± 0·024
M_{bol} (mag)	3·068 ± 0·058	3·533 ± 0·061
Distance (pc)	117·2 ± 2·3	

*https://stilism.obspm.fr

measurement to 115·8 ± 2·3 pc; this reddening is significantly more than the 0·023 ± 0·007 mag found by T08 from the interstellar sodium and potassium lines. The shorter distance could then be compensated by adopting larger $T_{\rm eff}$ values for the stars. The *Gaia* distance is questionable because the renormalized unit-weight error (RUWE) of 1·395 for V570 Per is near the maximum value of 1·4 for a reliable astrometric solution[27].

Summary and conclusions

V570 Per is a dEB containing two F-type stars on a 1·90-d circular orbit. The system shows shallow (0·12 and 0·11 mag) partial eclipses which were discovered using the *Hipparcos* satellite. We used *TESS* light-curves from two sectors and published RVs from T08 to determine its physical properties. The partial eclipses make a solution of the light-curve alone poorly determined, but the addition of a spectroscopic light ratio was sufficient to reach a determinate solution. The resulting radius measurements are relatively imprecise (2·3%) due to this, and in comparison with the mass measurements (0·5%). Our measured distance to the system is in reasonable agreement with that from *Gaia* DR3.

We compared the masses, radii, and $T_{\rm eff}$s of the stars to predictions from the PARSEC stellar evolutionary models[72]. The models provide a match to these properties to within the 1σ error bars for an age of 800–900 Myr and a slightly supersolar fractional metal abundance of $Z = 0{\cdot}020$ (where the solar value is $Z = 0{\cdot}017$).

We also found the eclipses to arrive 11 min later than expected in the *TESS* light-curves. Checks turned up no evidence for this being due to instrumental or data-reduction issues, so it may be an astrophysical effect. The system should be monitored for eclipse-timing variations caused by a possible third body. We also found residual systematics in the light-curve which we attribute to weak starspots rotating synchronously with the orbit. Twenty-four observations with the *Gaia Radial Velocity Spectrograph*[73] yielded a double-lined spectroscopic orbit for the system which is in partial agreement with the ground-based results from T08. Future observations with *Gaia* should allow the addition of more RV measurements to this analysis, plus direct access to the *Gaia* spectra for checking the discrepancy found for one of the two stars.

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★ https://www.cosmos.esa.int/gaia

† https://www.cosmos.esa.int/web/gaia/dpac/consortium

the *Gaia* Multilateral Agreement. The following resources were used in the course of this work: the NASA Astrophysics Data System; the *Simbad* database operated at CDS, Strasbourg, France; and the arχiv scientific paper preprint service operated by Cornell University.

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IS VZ LIBRAE A QUADRUPLE SYSTEM?

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Using new eclipse timings from the Harvard archive and published data, the period behaviour of VZ Lib is found to undergo both positive and negative discrete period changes between constant values. The modern eclipse timings support the suggestion that the system contains a third body with a period of 2·96 yr and minimum mass of 0·6 $M_\odot$, but further suggest a fourth body with a period of 16·4 yr and minimum mass of 0·09 $M_\odot$.

Introduction

VZ Librae is a relatively bright W Ursae Majoris system with $V \approx 10{\cdot}35$ at maximum and eclipse depths $\Delta V \sim 0^{\rm m}{\cdot}45$. The basic properties of the system, $P = 0^{\rm d}{\cdot}358$, $T_{\rm eff} \sim 5800$ K, and $q \sim 0{\cdot}3$ are all close to the median values for a sample of 700 W UMa stars listed by Latković *et al.*[1], and place the system firmly in the late-type population described by Jayasinghe *et al.*[2]. In common with a significant proportion of W UMa stars the VZ Lib system has been suspected of having a third, and possibly fourth component.

The variability of VZ Lib was discovered by Hoffmeister[3], who found a 'short-period', probably eclipsing, star with a photographic range of 10·0–10·5. Some twenty years later Tsesevich[4] classified the star as a W UMa-type variable and provided the first ephemeris based on visual observations made using a Graff photometer, between 1938 and 1944 at Odesa by himself and A.V. Solovyov. The first modern light-curve was provided by Claria & Lapasset[5] which notably showed a significant difference in the depths of the minima of $0^m{\cdot}06 \pm 0{\cdot}02$ (but this is not a simple measurement on the plot) and an obviously flattened secondary minimum. They also reported significant night-to-night variations in the light-curve but no O'Connell effect[6,7] above the $0^m{\cdot}01$ level. The first indication of a third body in the system came from the radial-velocity measurements of Lu *et al.*[8] (revised later[9]) who found the clear signature of an additional velocity component in their broadening functions. The movement of this component was followed over 1200 days — although there were only four broadly independent epochs — and varied from about –50 to –10 km s^{-1}, in a broadly sinusoidal manner. They also noted that the nightly scatter of perhaps 10 km s^{-1} exceeded 3σ which prompted them to consider if the companion was itself a close binary. The luminosity of the companion was estimated at $L_3/L_{12} = 0{\cdot}20 \pm 0{\cdot}04$ of the primary pair on the basis of its contribution to the broadening function; however, this was later revised to $L_3/L_{12} = 0{\cdot}045$ after taking into account the assumed later spectral type of the companion[10]. Zola *et al.*[11] (using Lu *et al.*'s velocities) gave the first photometric model which confirmed the flattened secondary eclipse, but in contrast to Claria & Lapasset, showed a significant O'Connell effect of $0^m{\cdot}02$–$0^m{\cdot}03$, and a much smaller difference between the two minima of $\sim 0^m{\cdot}01$. From the photometry they found a third-body light contribution of only 4–6% in V, R_c, and I_c. The photometric modelling of Szalai *et al.*[12] supports the larger third-light contribution of $L_3/L_{12} \approx 20\%$ in B and V, and their velocity cross-correlation profiles are consistent with this, but they found only a small difference in the minima, less than $0^m{\cdot}01$ in V. They also provide an additional velocity for the third component at $-4{\cdot}8 \pm 3$ km s^{-1}, slightly more positive than the highest value from Lu *et al.* that increased its velocity range, and they suggest that the third-body period is greater than the 1200-d span of Lu *et al.*'s data. Bonnardeau's[13] light-curve shows significant variation in the depth of secondary minimum in particular, and also changes in the O'Connell effect and a broader distortion of the maxima. Confusion over the third-light contribution continues with the two most recent photometric models as Yue *et al.*[14] find $L_3 = 1$–2% while Liao *et al.* find a larger contribution of 8–12%, in B, V, R_c, and I_c, but not as high as the 20% found earlier. The third-light contribution may depend on the inclusion of spots in some photometric solutions so the comparison is not simple. One clear point that emerges from the photometry is that the light-curve is very variable, with the presence or not of the O'Connell effect, and significant variation in the depths of the eclipses. As if to highlight this problem the solution of Liao *et al.* identifies what is clearly the flattened secondary eclipse as the primary, because it is the deeper of the two, and models the system accordingly. The system also shows a (true) negative O'Connell effect, most obviously in B, which is not reported in previous work.

Times of minima

The first published times of minimum date from 1937, a few years after Hoffmeister's discovery report, and continue to 1947, but these are visual, made by Solovyov and included in Tsesevich's work. The listed times are a mixture of observed minima and composite values, but individual observations are reported. Claria & Lapasset measured 20 times of minimum at seven epochs and derived the first modern ephemeris, which as they noted is not consistent with Tsesevich's ephemeris. Times of minima have been published by all the photometric studies mentioned above and many more individual timings published separately as listed by the O–C Gateway* and the Bundesdeutsche Arbeitsgemeinschaft für Veränderliche Sterne (BAV) Lichtenknecker-Database†. In addition Szalai *et al.* and Bonnardeau used minima derived from the Northern Sky Variability Survey (NSVS)[15] (no longer publicly available) and the All Sky Automated Survey (ASAS3)[16]. These data together with those from *Hipparcos* have been re-evaluated and new seasonal minima have been calculated using 2-harmonic Fourier fits with a fixed period. In a similar way minima have been measured from the much more extensive data of the All-Sky Automated Survey for Supernovae (ASAS-SN)[17,18]. Seasonal minima have been determined from 4-harmonic Fourier fits, but when there are sufficient data two timings have been measured per season with typically 100 points covering about 100 days. For all these data sets the times of minima have been calculated from the original UTC or (M)JD dates as appropriate, and the heliocentric corrections calculated using the Terrestrial Time (TT) date, and are within a few seconds of BJD_{TDB}.

As the star is relatively bright an attempt has been made to investigate its period behaviour prior to 1935 in the unexplored world of the early Harvard photographic data, which have been taken from the Digital Access to a Sky Century at Harvard (DASCH) archive‡. In view of the relatively low amplitude of the variation the observations were restricted to those with errors less than $0^{\mathrm{m}}\!\cdot 2$. The bulk of the data were taken between ~ 1890–1950 (JD 2412000–2435000), with the highest concentration in the latter third of this period. A much sparser set of observations covers the interval from ~ 1970–1990 (JD 2438000–2448000). Initially the observations were analysed in three sections: the early data prior to JD 2426000, the middle section JD 2426000–2435000, and the later data post-JD 2438000, which contain approximately 750, 820, and 285 data points, respectively. In terms of the other published data the middle section of the Harvard data is contemporaneous with the early visual observations and Tsesevich's ephemeris. The latter section covers the period of Claria & Lapasset's observations and the *Hipparcos* minima, but precedes all the other modern data.

To avoid any unexpected surprises a Discrete Fourier Transform (DFT) periodogram was applied to each section and in all three cases a clear and unambiguous peak appeared at the anticipated half-period of the binary. In addition to the main peak all the DFTs show noticeable aliases at $f \pm 0{\cdot}00274$, 0·0339, and 0·0366 c d^{-1}, corresponding to spacings of one year, 29·5 d, and 27·3 d. Shorter sets of 2000 d from the early and middle sections, and 4000 d from the late section were fitted with a least-squares 2-harmonic Fourier series based on the mean period to determine composite times of minimum for these segments of the data. A range of initial periods were fitted and these converged to give unambiguous periods for each section. The photographic light-curves are not sufficiently well determined to assign the minima so there is a potential

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

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

‡ DASCH https://library·cfa·harvard·edu/search-dasch

ambiguity of about half a period in the epoch zero of each ephemeris. The times of minima for the data prior to JD = 2451000 are given in Table I and cover the Harvard and visual data, Claria & Lapasset's photoelectric photometry (pep) data, and one discordant CCD timing. For reasons that will become clear, the times of minima of the modern data, post JD = 2451000, are given later in Table III.

TABLE I

Times of minimum from the data prior to HJD 2451000

HJD	*Error*	*Min.*	*Cycle*	*O–C (d) Ephemeris*	*O–C (d) Linear*	*Band/ Detector*	*Observer/Source*
2416960·6945	0·0021	2	−77674·5	−0·0088	−0·0040	pg	Harvard (This paper)
2416960·8746	0·0024	1	−77674·0	−0·0078	−0·0030	pg	Harvard (This paper)
2418764·9142	0·0023	2	−72638·5	−0·0014	−0·0053	pg	Harvard (This paper)
2418765·0926	0·0022	1	−72638·0	−0·0022	−0·0060	pg	Harvard (This paper)
2421010·5260	0·0025	2	−66370·5	0·0180	0·0034	pg	Harvard (This paper)
2421010·7076	0·0026	1	−66370·0	0·0204	0·0058	pg	Harvard (This paper)
2423181·8201	0·0025	1	−60310·0	0·0592	−0·0059	pg	Harvard (This paper)
2423181·9965	0·0029	2	−60309·5	0·0565	−0·0086	pg	Harvard (This paper)
2425379·2875	0·0018	2	−54176·5	0·1206	−0·0078	pg	Harvard (This paper)
2425379·4674	0·0019	1	−54176·0	0·1214	−0·0070	pg	Harvard (This paper)
2427519·9774	0·0020	2	−48201·5	0·1891	−0·0009	pg	Harvard (This paper)
2427520·1584	0·0020	1	−48201·0	0·1910	0·0010	pg	Harvard (This paper)
2428722·3468	0·0017	2	−44845·5	0·2279	0·0033	pg	Harvard (This paper)
2428722·5277	0·0019	1	−44845·0	0·2297	0·0051	pg	Harvard (This paper)
2428731·308	—	2	−44820·5	0·2326	0·0077	Vis.	A. V. Solovyov[4]
2428731·478	—	1	−44820·0	0·2235	−0·0014	Vis.	A. V. Solovyov[4]
2429046·215	—	2	−43941·5	0·2264	−0·0075	Vis.	A. V. Solovyov[4]
2429046·405	—	1	−43941·0	0·2373	0·0034	Vis.	A. V. Solovyov[4]
2429369·184	—	1	−43040·0	0·2214	−0·0219	Vis.	A. V. Solovyov[4]
2429645·010	—	1	−42270·0	0·1849	−0·0663	Vis.	Tsesevich[4]
2429645·192	—	2	−42269·5	0·1877	−0·0635	Vis.	Tsesevich[4]
2430493·286	—	2	−39902·5	0·2732	−0·0024	Vis.	A. V. Solovyov[4]
2430493·473	—	1	−39902·0	0·2811	0·0055	Vis.	A. V. Solovyov[4]
2430899·220	—	2	−38769·5	0·2953	0·0080	Vis.	Tsesevich[4]
2430899·399	—	1	−38769·0	0·2951	0·0079	Vis.	Tsesevich[4]
2431169·3567	0·0014	2	−38015·5	0·3017	0·0067	pg	Harvard (This paper)
2431169·5377	0·0015	1	−38015·0	0·3035	0·0085	pg	Harvard (This paper)
2431256·240	—	1	−37773·0	0·3062	0·0087	Vis.	Tsesevich[4]
2431256·426	—	2	−37772·5	0·3131	0·0155	Vis.	Tsesevich[4]
2432337·678	—	2	−34754·5	0·3274	−0·0013	Vis.	Solovyov[19]
2432712·4223	0·0023	2	−33708·5	0·3286	−0·0109	pg	Harvard (This paper)
2432712·6001	0·0026	1	−33708·0	0·3273	−0·0122	pg	Harvard (This paper)
2441102·4533	0·0042	1	−10290·0	0·3779	−0·0022	pg	Harvard (This paper)
2441102·6365	0·0038	2	−10289·5	0·3819	0·0019	pg	Harvard (This paper)
2444366·7339	—	2	−1178·5	0·3453	0·0016	*V*	Claria & Lapasset[5]
2444366·7359	—	2	−1178·5	0·3473	0·0036	*B*	Claria & Lapasset[5]
2444366·7362	—	2	−1178·5	0·3476	0·0039	*U*	Claria & Lapasset[5]
2444408·6509	—	2	−1061·5	0·3455	0·0023	*V*	Claria & Lapasset[5]
2444408·6514	—	2	−1061·5	0·3460	0·0028	*B*	Claria & Lapasset[5]
2444698·8448	—	2	−251·5	0·3464	0·0064	*V*	Claria & Lapasset[5]
2444698·8453	—	2	−251·5	0·3469	0·0069	*B*	Claria & Lapasset[5]
2444698·8464	—	2	−251·5	0·3480	0·0080	*U*	Claria & Lapasset[5]
2444787·5147	—	1	−4·0	0·3462	0·0072	*U*	Claria & Lapasset[5]
2444787·5154	—	1	−4·0	0·3469	0·0079	*V*	Claria & Lapasset[5]
2444787·5154	—	1	−4·0	0·3469	0·0079	*B*	Claria & Lapasset[5]
2444788·5899	—	1	−1·0	0·3466	0·0076	*B*	Claria & Lapasset[5]
2444788·5901	—	1	−1·0	0·3468	0·0078	*V*	Claria & Lapasset[5]
2444788·5901	—	1	−1·0	0·3468	0·0078	*U*	Claria & Lapasset[5]
2444789·6645	—	1	2·0	0·3464	0·0074	*U*	Claria & Lapasset[5]
2444789·6654	—	1	2·0	0·3473	0·0083	*V*	Claria & Lapasset[5]
2444789·6654	—	1	2·0	0·3473	0·0083	*B*	Claria & Lapasset[5]

TABLE I (*concluded*)

Times of minimum from the data prior to HJD 2451000

HJD	*Error*	*Min.*	*Cycle*	*O–C (d) Ephemeris*	*O–C (d) Linear*	*Band/ Detector*	*Observer/Source*
2444790·5598	—	2	4·5	0·3461	0·0071	*U*	Claria & Lapasset [5]
2444790·5603	—	2	4·5	0·3466	0·0076	*B*	Claria & Lapasset [5]
2444790·5608	—	2	4·5	0·3471	0·0081	*V*	Claria & Lapasset [5]
2446202·8116	0·0024	2	3946·5	0·3251	0·0018	pg	Harvard (This paper)
2446202·9910	0·0023	1	3947·0	0·3255	0·0022	pg	Harvard (This paper)
2448085·460	—	2	9201·5	0·3016	−0·0008	Vis.	O. Walas [20]
2448094·418	—	2	9226·5	0·3030	0·0008	Vis.	O. Walas [20]
2448122·361	—	2	9304·5	0·3015	−0·0004	Vis.	O. Walas [20]
2448323·3557	0·0012	2	9865·5	0·3106	0·0110	*Hp*	*Hipparcos* (This paper)
2448323·5328	0·0013	1	9866·0	0·3086	0·0089	*Hp*	*Hipparcos* (This paper)
2450635·960	—	2	16320·5	0·3274	0·0534	*V*	K. Nagai [21]

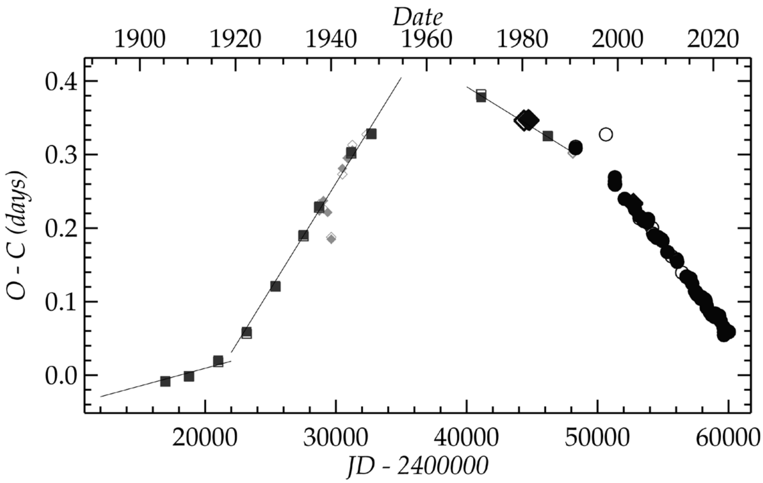

FIG. 1

O–C diagram of all the timing data of VZ Lib constructed using an arbitrary ephemeris. The different symbols identify the visual data (small diamonds), pg (squares), pep (large diamonds), and CCD photometry (circles). Open symbols identify secondary minima. The three ephemerides of the early, middle, and late Harvard data are shown as lines with the points showing the composite timings of the 2000-d sectors in the early and middle sections, and the 4000-d sectors in the late section. The ephemeris of the middle section is closely matched to the contemporaneous visual observations, and the third section aligns well with the early pep data. Also see Table III for additional details. The isolated visual points near JD = 2430000 come from Tsesevich's ephemeris which is essentially vertical in this plot. The data prior to JD = 2438000 could be placed half a cycle up or down in the O–C diagram.

Long-term period behaviour

The O–C diagram of all the data is shown in Fig. 1 and is constructed using an arbitrary ephemeris HJD = 2444788·6 + 0·358259 × *E*. The lines show the range and ephemeris of the three sections of Harvard data, while the points show the composite timings for the 2000-d and 4000-d sectors. While there is potential ambiguity in the placing of these three sections it is possible to reduce the uncertainty. The late section can be tied to Claria & Lapasset's pep data where the minima are positively identified. Although the periods are consistent within the errors, the ephemerides are significantly divergent over the time of the photographic data. The reason for this is probably because the pep data were taken over a short time interval. However, the ephemeris of the late section is consistent with the Claria & Lapasset and *Hipparcos* timings. The middle section can be tied to the visual data, but as has already been mentioned the visual data suffer from the same ambiguity so they both move together in the O–C diagram. The ephemerides of the middle section and the visual data are consistent within the errors and generate times of minima with an r.m.s. difference of $0^{d}\cdot002$. The placement of both in the O–C diagram depends entirely on the subjective notion of continuity with the following section. Adding half a cycle to the middle section leads to some contortions of the period but is not excluded by the data, while subtracting half a cycle is a realistic alternative, and would not require the inclusion of any other interpolating periods. The version given here is probably the least offensive but could be interpreted with or without an additional period bridging the gap in the data, and is the same spacing as used by Liao *et al.* There are no other observations that can be used to tie in the early section, but as there is no gap in the photographic data at this point, continuity arguments leave little room for movement, so it is tied to the middle section. The period of the early section is clearly shorter than the middle section so the general period behaviour cannot be interpreted as a secular change, and even in the sections that show a decreasing period, the residuals are not parabolic. In fact the long sections appear to be linear, so the most likely interpretation is discrete, positive and negative changes between constant periods. If there are just the four periods, as indicated on the O–C diagram, then the two central ones both last for about 14000 d, and this time-scale is also consistent with the recent data. The ephemerides of the different data subsets are listed in Table II and the times of minima themselves are listed in Table I. The O–C Ephemeris column in Table I is the residual from the plot ephemeris, while the O–C Linear column is the residual from the local linear photographic photometry (pg) ephemeris.

As mentioned above Tsesevich's ephemeris is not consistent with Claria & Lapasset's but it can now been seen that these derive from two different period sections of the O–C diagram. However, Tsesevich's ephemeris is also not consistent with the contemporaneous visual and photographic minima and is essentially vertical in the O–C diagram. Examining the difference between these periods leads to the conclusion that Tsesevich's period is the 1-year alias of the true period at the time, so at some point a half-cycle error was introduced between two seasons' data.

TABLE II

Photographic and visual ephemerides

Data	T_0	*Period*	*Range*
Harvard (Early)	2418213·371(2)	0·358265(3)	2412000 < JD < 2422000
Harvard (Middle)	2429163·557(1)	0·358273(2)	2422000 < JD < 2435000
Tsesevich	2429645·010	0·3584501	
Visual	2430493·470(2)	0·358274(1)	2428730 < JD < 2432338
Harvard (Late)	2443830·956(2)	0·358259(7)	2440000 < JD < 2448000
Claria & Lapasset	2444788·5901(1)	0·35826334(24)	

TABLE III

Times of minimum from data after HJD 2451000

HJD	Error	Min.	Cycle	O–C (d) Linear	O–C (d) LTTE	Band	Observer/Source
2451306·0232	0·0004	1	−13364·0	−0·0049	−0·0019	*Rc*	S. Kiyota [23]
2451311·0429	0·0014	1	−13350·0	−0·0008	0·0021	*V*	K. Nagai [23]
2451316·0641	0·0013	1	−13336·0	0·0049	0·0076	*V*	K. Nagai [23]
2451331·1014	0·0003	1	−13294·0	−0·0045	−0·0020	*Rc*	S. Kiyota [23]
2451336·6540	0·0006	2	−13278·5	−0·0048	−0·0025	*R*	NSVS (This paper)
2451336·8338	0·0005	1	−13278·0	−0·0042	−0·0018	*R*	NSVS (This paper)
2452070·5365	0·0011	1	−11230·0	−0·0066	−0·0009	*V*	ASAS3 (This paper)
2452070·7156	0·0012	2	−11229·5	−0·0066	−0·0009	*V*	ASAS3 (This paper)
2452725·4345	—	1	−9402·0	0·0023	0·0004	*C*	Qian *et al.* [22]
2452725·6135	—	2	−9401·5	0·0021	0·0002	*C*	Qian *et al.* [22]
2452726·5097	—	1	−9399·0	0·0027	0·0008	*C*	Qian *et al.* [22]
2452727·4050	—	2	−9396·5	0·0024	0·0004	*C*	Qian *et al.* [22]
2452727·5847	—	1	−9396·0	0·0029	0·0010	*C*	Qian *et al.* [22]
2452730·6304	—	2	−9387·5	0·0035	0·0016	*C*	Qian *et al.* [22]
2452761·0806	—	2	−9302·5	0·0020	0·0002	*Rc*	K. Nagai [24]
2452763·0500	—	1	−9297·0	0·0010	−0·0008	*Rc*	K. Nagai [24]
2452853·5063	0·0008	2	−9044·5	−0·0019	−0·0030	*V*	ASAS3 (This paper)
2452853·6857	0·0006	1	−9044·0	−0·0016	−0·0026	*V*	ASAS3 (This paper)
2453189·0102	—	1	−8108·0	−0·0033	0·0016	*BV*	Szalai *et al.* [12]
2453190·9776	—	2	−8102·5	−0·0063	−0·0014	*BV*	Szalai *et al.* [12]
2453438·8952	0·0003	2	−7410·5	−0·0008	0·0021	C	Krajci [25]
2453450·5387	0·0004	1	−7378·0	−0·0006	0·0020	*V Rc*	Zejda *et al.* [26]
2453509·8297	0·0006	2	−7212·5	−0·0007	0·0005	*C*	Ogłoza *et al.* [27]
2453511·6204	0·0010	2	−7207·5	−0·0012	−0·0001	*C*	Ogłoza *et al.* [27]
2453511·7985	0·0002	1	−7207·0	−0·0023	−0·0012	*C*	Ogłoza *et al.* [27]
2453517·7113	0·0001	2	−7190·5	−0·0007	0·0003	*C*	Ogłoza *et al.* [27]
2453800·0188	0·0009	2	−6402·5	0·0023	−0·0021	*V*	ASAS3 (This paper)
2453800·1987	0·0009	1	−6402·0	0·0031	−0·0013	*V*	ASAS3 (This paper)
2453858·2414	—	1	−6240·0	0·0086	0·0042	*Ic*	K. Nagai [28]
2453860·0311	—	1	−6235·0	0·0070	0·0026	*V*	K. Nagai [28]
2454164·3650	0·0005	2	−5385·5	0·0037	0·0044	*C*	Qian *et al.* [22]
2454233·502	0·0015	2	−5192·5	−0·0024	−0·0006	*BV*	Bonnardeau [13]
2454301·3905	0·0020	1	−5003·0	−0·0031	−0·0007	*BV*	Bonnardeau [13]
2454526·7345	0·0007	1	−4374·0	−0·0011	−0·0010	*V*	ASAS3 (This paper)
2454526·9134	0·0007	2	−4373·5	−0·0014	−0·0012	*V*	ASAS3 (This paper)
2454539·6335	0·0005	1	−4338·0	0·0007	0·0006	*V*	Bonnardeau [13]
2454571·1601	—	1	−4250·0	0·0009	0·0000	*Ic*	K. Nakajima [29]
2454644·4240	0·0010	2	−4045·5	0·0018	−0·0009	*V*	Bonnardeau [13]
2454646·3950	0·0003	1	−4040·0	0·0024	−0·0004	*V*	Bonnardeau [13]
2454656·4265	0·0015	1	−4012·0	0·0027	−0·0002	*V*	Bonnardeau [13]
2454667·3522	0·0001	2	−3981·5	0·0017	−0·0016	*C*	F. Salvaggio [30]
2454667·3531	0·0007	2	−3981·5	0·0026	−0·0007	*C*	F. Salvaggio [31]
2454894·6686	0·0010	1	−3347·0	0·0056	−0·0008	*V*	Bonnardeau [13]
2454920·2831	—	2	−3275·5	0·0049	−0·0015	*V*	K. Nakajima [32]
2454951·0928	—	2	−3189·5	0·0048	−0·0015	*Ic*	K. Nagai [32]
2454971·5140	0·0010	2	−3132·5	0·0054	−0·0007	*V*	Bonnardeau [13]
2455318·1183	—	1	−2165·0	−0·0014	−0·0007	*Ic*	K. Nagai [33]
2455350·0036	—	1	−2076·0	−0·0008	0·0003	*Ic*	K.Nagai [33]
2455652·9091	0·0006	2	−1230·5	0·0006	−0·0004	*V*	R. Diethelm [34]
2456016·9007	0·0001	2	−214·5	0·0056	0·0002	*V*	R. Diethelm [35]
2456053·0829	—	2	−113·5	0·0041	−0·0010	*Ic*	K. Nagai [36]
2456067·4138	0·0003	2	−73·5	0·0049	0·0000	*B*	M. Lehky [37]
2456067·4139	0·0002	2	−73·5	0·0049	0·0000	*V*	M. Lehky [37]
2456067·4140	0·0003	2	−73·5	0·0051	0·0002	*Rc*	M. Lehky [37]
2456067·4146	0·0002	2	−73·5	0·0057	0·0008	*Ic*	M. Lehky [37]
2456093·7440	0·0004	1	0·0	0·0034	−0·0011	*V*	R.Diethelm [35]
2456457·9039	0·0007	2	1016·5	−0·0024	0·0009	*V*	ASAS-SN (This paper)
2456781·0511	—	2	1918·5	−0·0007	−0·0001	*Ic*	K. Nagai [38]
2456788·2172	—	2	1938·5	0·0003	0·0007	*V*	H. Itoh [38]

TABLE III (*continued*)

Times of minimum from data after HJD 2451000

HJD	*Error*	*Min.*	*Cycle*	*O–C (d) Linear*	*O–C (d) LTTE*	*Band*	*Observer/Source*
2456827·8048	0·0006	1	2049·0	0·0008	0·0004	*V*	ASAS-SN (This paper)
2456827·9833	0·0005	2	2049·5	0·0001	–0·0003	*V*	ASAS-SN (This paper)
2457099·7241	0·0004	1	2808·0	0·0049	0·0022	*V*	ASAS-SN (This paper)
2457099·9026	0·0003	2	2808·5	0·0043	0·0016	*V*	ASAS-SN (This paper)
2457164·0274	—	2	2987·5	0·0016	–0·0004	*Ic*	K. Nagai[39]
2457223·4971	0·0004	2	3153·5	0·0010	0·0002	*V*	ASAS-SN (This paper)
2457223·6761	0·0006	1	3154·0	0·0009	0·0001	*V*	ASAS-SN (This paper)
2457440·9524	0·0004	2	3760·5	–0·0041	0·0003	*V*	ASAS-SN (This paper)
2457441·1316	0·0004	1	3761·0	–0·0041	0·0003	*V*	ASAS-SN (This paper)
2457527·1119	—	1	4001·0	–0·0048	0·0009	*V*	K. Nagai[40]
2457527·1126	—	1	4001·0	–0·0041	0·0016	*B*	K. Nagai[40]
2457527·1133	—	1	4001·0	–0·0034	0·0023	*Ic*	K. Nagai[40]
2457591·7761	0·0004	2	4181·5	–0·0055	0·0007	*V*	ASAS-SN (This paper)
2457591·9563	0·0005	1	4182·0	–0·0044	0·0018	*V*	ASAS-SN (This paper)
2457819·9867	0·0005	2	4818·5	–0·0030	0·0006	*V*	ASAS-SN (This paper)
2457820·1659	0·0005	1	4819·0	–0·0029	0·0007	*V*	ASAS-SN (This paper)
2457901·4888	0·0004	1	5046·0	–0·0038	–0·0020	*R*	Yue *et al.*[14]
2457901·4891	0·0004	1	5046·0	–0·0035	–0·0018	*I*	Yue *et al.*[14]
2457901·4892	0·0002	1	5046·0	–0·0034	–0·0017	*V*	Yue *et al.*[14]
2457901·4894	0·0002	1	5046·0	–0·0032	–0·0015	*B*	Yue *et al.*[14]
2457901·6690	0·0004	2	5046·5	–0·0027	–0·0010	*B*	Yue *et al.*[14]
2457901·6691	0·0002	2	5046·5	–0·0026	–0·0009	*V*	Yue *et al.*[14]
2457901·6691	0·0003	2	5046·5	–0·0026	–0·0009	*I*	Yue *et al.*[14]
2457901·6692	0·0003	2	5046·5	–0·0025	–0·0008	*R*	Yue *et al.*[14]
2457907·7604	0·0007	2	5063·5	–0·0016	0·0000	*I*	Yue *et al.*[14]
2457907·7608	0·0006	2	5063·5	–0·0013	0·0003	*R*	Yue *et al.*[14]
2457907·7608	0·0007	2	5063·5	–0·0013	0·0003	*V*	Yue *et al.*[14]
2457907·7613	0·0009	2	5063·5	–0·0007	0·0009	*B*	Yue *et al.*[14]
2457959·7076	0·0004	2	5208·5	–0·0013	–0·0008	*V*	ASAS-SN (This paper)
2457959·8882	0·0004	1	5209·0	0·0001	0·0006	*V*	ASAS-SN (This paper)
2458190·7847	0·0002	2	5853·5	0·0016	0·0002	*g*	ASAS-SN (This paper)
2458190·9635	0·0003	1	5854·0	0·0013	–0·0001	*g*	ASAS-SN (This paper)
2458206·9063	0·0006	2	5898·5	0·0018	0·0005	*V*	ASAS-SN (This paper)
2458207·0865	0·0005	1	5899·0	0·0028	0·0016	*V*	ASAS-SN (This paper)
2458250·2536	0·0001	2	6019·5	0·0003	–0·0005	*BVRI*	Liao *et al.*[41]
2458256·1668	0·0001	1	6036·0	0·0022	0·0015	*BVRI*	Liao *et al.*[41]
2458274·6146	0·0003	2	6087·5	0·0000	–0·0005	*g*	ASAS-SN (This paper)
2458274·7934	0·0003	1	6088·0	–0·0003	–0·0007	*g*	ASAS-SN (This paper)
2458335·6916	0·0004	1	6258·0	–0·0054	–0·0047	*V*	S. Cook[42]
2458358·4424	0·0005	2	6321·5	–0·0037	–0·0026	*V*	ASAS-SN (This paper)
2458358·6220	0·0008	1	6322·0	–0·0032	–0·0021	*V*	ASAS-SN (This paper)
2458560·4960	0·0003	2	6885·5	–0·0056	–0·0003	*g*	ASAS-SN (This paper)
2458560·6749	0·0003	1	6886·0	–0·0059	–0·0006	*g*	ASAS-SN (This paper)
2458706·6637	0·0003	2	7293·5	–0·0058	0·0002	*g*	ASAS-SN (This paper)
2458706·8422	0·0003	1	7294·0	–0·0064	–0·0004	*g*	ASAS-SN (This paper)
2458917·6776	0·0006	2	7882·5	–0·0038	–0·0013	*g*	ASAS-SN (This paper)
2458917·8576	0·0006	1	7883·0	–0·0029	–0·0004	*g*	ASAS-SN (This paper)
2458946·1590	—	1	7962·0	–0·0036	–0·0018	*Ic*	K. Nagai[43]
2458946·1610	—	1	7962·0	–0·0016	0·0002	*B*	K. Nagai[43]
2458946·1610	—	1	7962·0	–0·0016	0·0002	*V*	K. Nagai[43]
2458965·1472	—	1	8015·0	–0·0029	–0·0016	*Ic*	K. Nagai[43]
2458965·1474	—	1	8015·0	–0·0027	–0·0014	*V*	K. Nagai[43]
2458965·1501	—	1	8015·0	0·0000	0·0013	*B*	K. Nagai[43]
2458993·9920	—	2	8095·5	0·0024	0·0030	*Ic*	K. Nagai[43]
2458999·0070	—	2	8109·5	0·0019	0·0023	*Ic*	K. Nagai[43]
2459042·7114	0·0005	2	8231·5	–0·0008	–0·0014	*g*	ASAS-SN (This paper)
2459042·8916	0·0005	1	8232·0	0·0003	–0·0003	*g*	ASAS-SN (This paper)
2459264·2960	—	1	8850·0	0·0034	0·0003	*Ic*	K. Nagai[44]
2459264·2980	—	1	8850·0	0·0054	0·0023	*B*	K. Nagai[44]
2459292·2390	—	1	8928·0	0·0026	–0·0004	Hα	K. Nagai[44]

TABLE III (*concluded*)

Times of minimum from data after HJD 2451000

HJD	*Error*	*Min.*	*Cycle*	*O–C (d) Linear*	*O–C (d) LTTE*	*Band*	*Observer/Source*
2459292·2400	—	1	8928·0	0·0036	0·0006	*B*	K. Nagai[44]
2459292·2430	—	1	8928·0	0·0066	0·0036	*U*	K. Nagai[44]
2459307·4659	0·0003	2	8970·5	0·0037	0·0008	*g*	ASAS-SN (This paper)
2459307·6459	0·0003	1	8971·0	0·0045	0·0016	*g*	ASAS-SN (This paper)
2459407·7752	0·0005	2	9250·5	0·0017	0·0002	*g*	ASAS-SN (This paper)
2459407·9544	0·0003	1	9251·0	0·0018	0·0003	*g*	ASAS-SN (This paper)
2459628·2770	—	1	9866·0	–0·0021	0·0006	*V*	K. Nagai[45]
2459628·2780	—	1	9866·0	–0·0011	0·0016	*Ic*	K. Nagai[45]
2459651·1960	—	1	9930·0	–0·0114	–0·0084	*Ic*	K. Nagai[45]
2459651·2000	—	1	9930·0	–0·0074	–0·0044	*V*	K. Nagai[45]
2459671·0876	0·0003	2	9985·5	–0·0029	0·0003	*g*	ASAS-SN (This paper)
2459671·2681	0·0003	1	9986·0	–0·0016	0·0016	*g*	ASAS-SN (This paper)
2459764·5938	0·0004	2	10246·5	–0·0011	0·0025	*g*	ASAS-SN (This paper)
2459764·7729	0·0004	1	10247·0	–0·0011	0·0024	*g*	ASAS-SN (This paper)
2460026·6598	0·0003	1	10978·0	0·0017	0·0008	*g*	ASAS-SN (This paper)
2460026·8396	0·0004	2	10978·5	0·0025	0·0015	*g*	ASAS-SN (This paper)

Recent period behaviour

Szalai *et al.*[12] gave the first, if limited, O–C diagram of the modern data (see Table III) which suggested a range of perhaps $0^{d}·015$ on a time-scale of > 1200 d. Qian *et al.*[22], using published and new timings, found a cyclic variation in the O–C residuals with $P_3 = 17·1$ yr and a light-travel-time-effect (LTTE) amplitude $A = 0^{d}·0200$, which implies a minimum mass of the third body of $m_3 \approx 1·1\ M_{\odot}$. Given the low luminosity of the companion they suggest that it must be a binary with low-mass components. However, their O–C diagram is given in cycles and the period corresponds to ~ 36000 cycles, which equals 35 years, not 17. Also, it has to be said that the phase coverage of this orbit is sparse, and it relies critically on Tsesevich's timing. The same is true of Bonnardeau's third-body orbit which uses a slightly different set of timings and finds an elliptical orbit, $e = 0·31$, with $P_3 = 35$ yr and a similar LTTE amplitude, but is broadly consistent with Qian *et al.*'s solution. More recent solutions have the benefit of more timing data and Yue *et al.* also incorporate the early visual timings in an effort to extend the base line, but they exclude Tsesevich's timing. They find a similar LTTE amplitude of $A = 0^{d}·0249$ but a much longer period $P_3 = 49$ yr, and an eccentric orbit with $e = 0·26$. However, although their solution passes through the visual timings it cannot be said to be consistent with them. The solution to this particular problem was suggested by Liao *et al.* who found that if the cycle count between the visual and modern data was increased and a secular period change introduced then the need for a long-period LTTE variation disappeared and the visual data became less of an issue. However, the problem is more complicated than this as the primary and secondary minima are indistinguishable in the visual data so the correct identification is impossible. As discussed earlier, the true offset between the visual and modern data could be ½, 1, or 1½ cycles. Nevertheless, Liao *et al.* also found a low-amplitude, short-period LTTE variation in the residuals from the secular change with $P_3 = 2·96 \pm 0·04$ yr and $A = 0^{d}·0039 \pm 0·0004$, implying a minimum mass $m_3 = 0·52 \pm 0·07\ M_{\odot}$, which is more compatible with the luminosity constraints.

However, given the period changes of the system shown earlier, all the solutions using minima prior to JD = 2450000 can be dicarded, except Liao *et al.* who reduced the impact of these by removing a secular change, although this will have introduced a small false variation into the modern data. As there is no evidence for a secular term, the data since JD = 2450000 have been treated as having a constant period and the residuals were tested for any periodic behaviour using the DFT periodogram. The dominant feature appeared at 1085 d, which is the same as found by Liao *et al.*, with a weaker feature at 25 d above the noise level. The observed times of minimum from JD = 2451000 (see Fig. 2) are fitted to the usual linear form of the ephemeris for the eclipsing binary, plus an offset due to the light-travel-time effect (LTTE) of the companion using the expression given by Irwin[46,47]. The fitting was performed using Markwardt's implementation of the Levenberg–Marquardt algorithm through MPFIT[48]. All the relevant details are given in a previous paper[49]. The initial LTTE solution was assumed to be circular and found $P_3 = 1090$ d with an amplitude of $A = 0^{d}\cdot0042$, but the residuals from this solution showed a clear systematic sinusoidal run, with about half the previous amplitude and a period near 6000 d, which is uncomfortably close to the span of the data. Given the possibility that

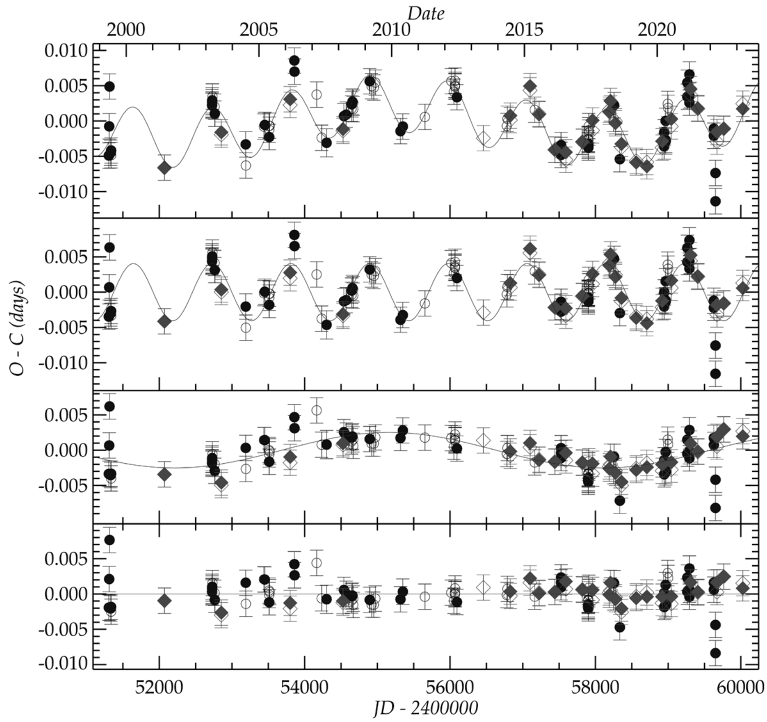

FIG. 2

O–C diagram of the pep and CCD timing data of VZ Lib after JD = 2451000 constructed using the linear ephemeris given in Table IV. Diamonds identify the ASAS3 and ASAS-SN minima while all the other timings are shown by circles. Open symbols identify secondary minima. The top panel shows the residuals from the linear ephemeris with the line giving the combined linear and two-component LTTE fit as given in Table IV. The second and third panels show the individual contributions of the third and fourth bodies, respectively. The bottom panel shows the residuals from the full fit in the top panel. The O–C residuals shown in the top panel and the residuals from the full LTTE solution are listed with the times of minima in Table III. The error bars are those used in the fit and not the measured ones.

this is a secular change, the solution was recalculated including a quadratic term, but although the amplitude of the residuals was reduced, the sinusoidal trend remained.

The other point to emerge is that the short-term scatter is relatively large, much larger than the formal errors, and may reflect the impact of the changes in the light-curves on the eclipse timings. So as not to assign unrealistic weights to the points, a minimum error of $0^{\rm d}{\cdot}0018$ was used in the solutions, and this leads to a reduced chi-squared $\chi^2_v \sim 1$, but as all the timings have smaller, or unknown errors, the solution is effectively unweighted. As there are apparently four bodies in the system the timings are now fitted with a linear ephemeris and two LTTE terms for the third and fourth bodies:

$$HJD = T_0 + P_0 \times E + \tau_3 + \tau_4.$$

Solutions were derived for different combinations of circular and elliptical orbits but none were found with significant eccentricities. The combined circular solutions are given in Table IV together with the parameters derived from the mass function, $m_{3,4} \sin^3 i$, the minimum masses, and $K_{3,4}$, the velocity imparted to the binary by the third and fourth bodies. The minimum masses of the components have been calculated assuming that the mass of the binary lies in the range 1·4–1·9 $M_\odot$[8,11,12] as $m_3 = 0{\cdot}6$ and $m_4 = 0{\cdot}09\ M_\odot$. The expected luminosity of the binary from the cool W UMa population period–luminosity calibrations suggests $M_V = 3{\cdot}9$–$4{\cdot}2$[2,50]. The distance to VZ Lib is $d = 180 \pm 4$ pc from Bailer-Jones *et al.*[51], but despite this the reddening is significant with $E_{B-V} = 0{\cdot}09 \pm 0{\cdot}02$ from Green *et al.*[52] and $E_{B-V} = 0{\cdot}07 \pm 0{\cdot}03$ from Lallement *et al.*[53]. Assuming a mean magnitude of $V = 10{\cdot}35$ and $R_V = 3{\cdot}1$ then the observed absolute magnitude $M_V = 3{\cdot}9$, which is consistent with the brighter end of the expected luminosity. According to the Rochester calibration (see Pecaut & Mamajek[54]) a main-sequence star with $m = 0{\cdot}6\ M_\odot$ has $M_V = 8{\cdot}5$ and $T_{\rm eff} = 4000$ K. If the system has $M_V = 3{\cdot}9$ then the contribution of the third body to the luminosity is at most ~ 2%, while the observed contribution is generally near 5% but in some cases it has been measured at 10% and even 20%, so there appears to be a luminosity deficit.

TABLE IV

Circular light-travel-time solutions

Parameter		*Third body*	*Fourth body*
T_0 (HJD)	=	2456093·74063(19)	
P_0 (d)	=	0·358254455(29)	
$A_{3,4}$ (d)	=	0·00405(24)	0·00252(26)
$e_{3,4}$	=	0·0 (fixed)	0·0 (fixed)
$\omega_{3,4}$ (°)	=	0·0 (fixed)	0·0 (fixed)
$T_{3,4}$ (HJD)	=	2456788 ± 9	2453685 ± 133
$P_{3,4}$ (d)	=	1083 ± 5	5994 ± 225
$a_{12} \sin i$ (AU)	=	0·70(4)	0·43(4)
$f(m)_{3,4}$ ($M_\odot$)	=	0·039	0·00032
$m_{3,4} \sin_3 i$ ($M_\odot$)	=	0·52–0·63	0·089–0.108
$K_{12(3,4)}$ (km s^{-1})	=	7·0	0·80
χ^2_v	=	1·034	

The velocity imparted to the binary by the third body is 7 km s^{-1}, and if this is combined with the mass ratio of the third body to the binary $q_3 = 0{\cdot}35$–$0{\cdot}39$, then this implies a velocity amplitude $K_3 = 19$ km s^{-1}, which is entirely consistent with the variation from –50 to –5 km s^{-1} of Lu *et al.*'s third component. Also, P_3 is consistent with the time-scale of their velocity variation, and the maximum velocity near JD = 2451700 (see Fig. 5 of Lu *et al.*) broadly coincides with the zero point of the third-body orbit in Fig. 2.

Summary

Close binary stars are frequently found in multiple systems[55,56], with up to about 60%[1,57,58] for short-period systems. The median third-body period P_3 ~ 10 years but have been seen as short as 2 years[1] so the 3 years for VZ Lib is not that extreme. In systems with two additional bodies these may be arranged individually or in a 2+2 hierarchy, but in these cases both binaries tend to have similar masses[56,59]. VZ Lib presents a consistent picture of a W UMa binary with two additional bodies with periods of 2·96 and 16·4 yr and minimum masses of 0·6 and 0·09 $M_{\odot}$, respectively. A search for periodic components in the residuals from the linear ephemeris of the recent data down to the limit of one day found only the 2·96-yr and the much weaker 25-d features above the noise. Removal of the 2·96-yr component then revealed the longer-period, weaker fourth component, which is entirely consistent with a very low-mass body in the system. However, the reason for the question in the title is that there are some persistent inconsistencies. The first is scatter of the O–C residuals which is substantially larger than the formal errors. While that is not unusual in these systems, and is probably due to obvious changes in the shape of the light-curve, in this case the amplitude and time-scale does seem extreme. Secondly there is the similar situation with the scatter in the velocities of the third component reported by Lu *et al.*, which led them to consider if their third body was a binary. Finally, there is the luminosity deficit which suggests that the system should contain a brighter component than a 0·6-$M_{\odot}$ main-sequence star.

If these questions are going to be answered then more observations will be required. The system needs a modern velocity solution and that should be taken to sample the 2·96-yr cycle so that the third-body orbit can be redefined. More intensive photometric monitoring is also required to define better the third-body excursions in the O–C diagram, and characterize the short-term variations in the light-curve.

Acknowledgements

The author is pleased to acknowledge the valuable assistance of Sian Prosser and staff of the RAS Library in accessing Tsesevich's work; also the use of the NASA/ADS, the *Simbad* database and the VizieR catalogue access tool. This work has made use of data from the European Space Agency (ESA) mission *Gaia* (https://www.cosmos.esa.int/gaia), processed by the *Gaia* Data Processing and Analysis Consortium (DPAC). The author also gratefully acknowledges the Czech Astronomical Society and the Bundesdeutsche Arbeitsgemeinschaft für Veränderliche Sterne for supporting the O–C Gateway and the BAV Lichtenknecker-Database, respectively.

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REVIEWS

Gravity. From Falling Apples to Supermassive Black Holes, 2nd Edition, by Nicholas Mee (Oxford University Press), 2022. Pp. 360, 20 × 14 cm. Price £18·99 (hardbound; ISBN 978 0 19 284528 3).

The second edition of Nicholas Mee's book, *Gravity*, is a very readable, expository survey of the history of science leading to our current state of knowledge in astrophysics. It incorporates both established paradigms and speculations that continue explorations seeking a consistent and experimentally viable model of the observable Universe. The style is accessible and reveals both political intrigues and personal tragedy that sometimes lie behind the progress of scientific endeavour. For example, the author recounts how the young astronomer Jeremiah Horrocks, who died unrecognized at the age of 26, provided critical experimental evidence that ultimately guided Newton in his formulation of a Universal Theory of Gravitation,

The author's descriptions of many counter-intuitive concepts in Special and General Relativity are concise and cover a broad area of modern physics. The initiated might raise an eyebrow on his explanation of why matter cannot, according to Einstein, break the 'light barrier', but this does not detract from the overall impression of a well-crafted and beautifully illustrated book on popular science. — Robin Tucker.

A Traveler's Guide to the Stars, by Les Johnson (Princeton University Press), 2023. Pp. 219, 22·5 × 15 cm. Price £22/$27·95 (hardbound; ISBN 978 0 691 21237 1).

Many astronomers have an interest in science fiction, but need to suspend their disbelief as they read about, or watch, the amazing interstellar voyages depicted in the stories or films. We instinctively know that such voyages are not currently possible, but we might be hard pressed to explain why. This book explains very clearly. The author led NASA's short-lived Interstellar Propulsion Technology Research Project from 1999–2001 and, to quote his Preface, "I came to believe that going to the stars is something that can actually be done". As a result, he continued in his spare time to work on the project, founding what became the Interstellar Research Group (see www.irg.space).

This book distils his research into the options for interstellar travel into a readable, if slightly pessimistic, review of all the different possible propulsion methods, giving a clear and realistic account of all the difficulties involved in realizing them, not least of which is the danger from impacts from interstellar dust once the spacecraft has reached a substantial fraction of the speed of light, as would be necessary for flight to even the nearest stars. To quote Douglas Adams, "Space … is big. Really big. … mind-bogglingly big …".

The current system for short-range exploration within the Solar System is of course the chemical rocket, but that is completely inadequate for interstellar travel where continuous acceleration to 0·1*c* or more is needed. Solar sails might do, but what happens when the Sun is no longer a useful energy source? Johnson mentions high-power lasers as a possible replacement for the Sun, but even they have a limited range. Nuclear-fusion power would work, but even there the issue of carrying enough fuel limits the distance to be travelled, unless the spacecraft can continually pick up hydrogen from the interstellar medium; given the low H density in space, that would require an enormous collector (hundreds or even thousands of miles across). Ion thrusters would be effective once the spacecraft is well outside the gravitational influence of the Sun, so perhaps a succession of methods of propulsion might be used. And of course if the spacecraft is intended to land on a distant object it has to slow down again, which also requires fuel. Having to carry fuel increases the mass of the craft, which in turn requires more fuel to propel it … .

Johnson covers all these aspects and many more in great detail, not forgetting the engineering challenges, and makes it very clear that even the most promising propulsion systems will be very difficult to manufacture in practice. In the final sentence of the Epilogue, he concludes: "Interstellar travel is clearly possible, and making it happen will be extremely difficult — but it can be done!" In the final chapter of the book, he analyses some science-fiction from a similarly careful perspective, showing why (for example) warp drive is not physically possible, but points out that many real space pioneers have been inspired to undertake their work by the vision of science-fiction writers.

This is an unusual book, a sober and careful analysis of the possibility of interstellar travel, written by someone with exactly the right background. If you feel slightly guilty that you enjoy science fiction, this book is for you! I thoroughly enjoyed reading it. — ROBERT CONNON SMITH.

Back to the Moon. The Next Giant Leap for Humankind, by Joseph Silk (Princeton University Press), 2022. Pp. 292, 22·5 × 15 cm. Price £25/$29·95 (hardbound; ISBN 978 0 691 21523 5).

This book is certainly timely: we are witnessing another space race. The *Artemis* and *Chang'e* programmes are well underway and other nations have launched probes to the Moon with varying success. Nearer home, the Royal Society hosted a two-day Discussion Meeting 'Astronomy from the Moon: the next decades', on 2023 February 13–14, organised by Silk and colleagues, having earlier published a related series of articles*. *Back to the Moon* is a forceful pitch aimed at a general readership for lunar exploitation and the inclusion of astronomy as a small part of developments over the next decades, 'riding on the coat tails' of mining and tourism, not to mention political competition.

The first three chapters give the background to the new space race and the science. Much of the development envisaged depends on the mining of lunar water; will it be easy and cheap enough to provide water for industrial purposes as well as supporting life at a lunar station? I would have liked to have read more about lunar dust and its use with water to make building bricks (p. 69) able to withstand lunar conditions such as the extreme day–night temperature range. The extensive use of ever more capable robots is envisaged but I would challenge the view (p. 71) that the communication time delay to Earth of about one-and-a-quarter seconds makes local control essential.

The central chapters (4–8) delve into astronomical questions and the great advantages of making observations from the lunar surface. The reader is introduced to the uncertainty of the earliest Universe and how cold, dark hydrogen clouds could be observed by their absorption against the CMB in the 21-cm line red-shifted to wavelengths observable only from above the Earth's ionosphere, and preferably from the far side of the Moon where the observatory would be shielded from radio signals generated on the Earth. The story continues with detailed measurement of the CMB, black holes, and a lunar gravitational-wave detector, followed by the search for biosignatures from exoplanets. Considering the search for extra-terrestrial life, the author reminds us of the great uncertainties in the terms making up the Fermi-paradox equation and also the possibility that advanced technological civilizations, including our own, may have relatively short lives, owing to either self-inflicted or natural catastrophic events.

Astronomy from the Moon: the next decades, Phil. Trans. R. Soc. A,* Volume **379, Issue 2188, 2021, access at: https://royalsocietypublishing.org/toc/rsta/2021/379/2188. Another issue of *Phil. Trans.* including the papers given at the meeting is planned.

The competition and possible conflicts for resources on the Moon are of serious concern (Ch. 9). For example, the deepest, permanently shadowed and very cold polar craters are the most promising sites for mining lunar water — but are also the best sites for locating telescopes, especially for observing in the infrared, which would be vulnerable to dust thrown up by the mining. Also, although the lack of atmosphere saves the Moon from the dust storms occurring on Mars, it ensures that the dust thrown up by spacecraft landings and takings off will be distributed over a large area, impacting other facilities. Other potential sources of conflict would arise from mining for rare earths, if these turn out to be concentrated in only a few economically viable regions. One must agree with the author that, with the emerging new space race, it is especially urgent to set up an enforceable framework for regulatory control*. The final chapter paints a rosy view of life on the Moon provided that conflicts are avoided.

Each chapter is accompanied by substantial end notes, which I found very useful, along with extensive bibliographies and suggestions for further reading. The exploitation of the Moon in the next decade should be of wide general interest and this book will help inform that. — Peredur Williams.

Outer Space: 100 Poems, edited by Midge Goldberg (Cambridge University Press), 2022. Pp. 177, 20·5 × 13·5 cm. Price £12·99/$16·99 (hardbound; ISBN 978 1 009 20360 9).

Poetry is nothing without the subjective choices of the poet — in apparent contrast to astronomy's claim to objective truth. But, as the editor of this judiciously selected anthology comments, both fields of human endeavour are inspired by the questions "where did we come from, why are we here, where are we going?" And of course, some poets are astronomers as well. Edmund Halley's panegyric 'On the incomparable Isaac Newton' (originally written in Latin and translated here by Deborah Warren), and chock-full of scientific allusions, is included here, as is 'Carnal Knowledge', a poem by Rebecca Elson, who worked on globular clusters and analysed some of the first data from the *HST* before her untimely death in 1999. (I highly recommend her posthumous collection *A Responsibility to Awe*, published by Carcanet Press.)

This isn't the first such anthology, the earlier *Dark Matter: Poems of Space* (edited by Maurice Riordan and Jocelyn Bell Burnell, and published by Gulbenkian in 2008) contains specially commissioned poems, as well as essays considering the process of writing creatively about astronomy. Pleasingly, there is very little overlap between the two books.

An over-generalization: anthologies tend to showcase variety and only include short excerpts from longer works, which can lessen their impact. Excerpts from Gwyneth Lewis' 'Zero Gravity: A Space Requiem' are frequently anthologized in books about poetry and science, but this lengthy poem based on the death of her sister-in-law and her astronaut cousin's space-shuttle flight only reveals its full emotional power when read in its entirety, as it is here, and for which I commend the editor.

The works are arranged chronologically, allowing us to appreciate how poets' opinions of the night sky have changed over the centuries. I read the anthology trying to spot when poets started to notice technology, and found Wordsworth

*The establishment of military bases on the Moon is considered in Chapter 11 of *The Human Factor in the Settlement of the Moon: An Interdisciplinary Study*, reviewed in *The Observatory*, **142**, 182, 2022; see also the letter by Corbally in *The Observatory*, **143**, 35, 2023.

referring explicitly to "A Telescope upon its frame… Long is it as a barber's pole, or mast of little boat" in his 1806 poem 'Star-Gazers'. But already the technology is proving to be a disappointment, "they who pry and pore/ Seem to meet with little gain, seem less happy than before".

Although the anthology (perhaps inevitably) leans towards the Anglophone world, the editor has sourced some works by indigenous peoples around the world. 'The Song of the Stars' (from the Passamaquoddy people in north-east America and translated in the 19th Century by Charles Godfrey Leland) has an unusual point of view — looking down from the heavens at Earth, thus demonstrating poetry's power: "we are the stars which sing". — PIPPA GOLDSCHMIDT.

I Never Call It Big Bang. George Gamow — The Extraordinary Story of a Genius of Physics, by Alessandro Bottino & Cristina Favero (World Scientific), 2022. Pp. 170, 23·5 × 16 cm. Price £30 (hardbound; ISBN 978 981 12430 4).

This biography of the physicist George Gamow (1904–1968) is like no other. Gamow's life is mostly written in the present tense, adding immediacy to the story of a picaresque genius whose limited attention span liberated his innate ethereal curiosity. Gamow had no time for the tedium (as he saw it) of in-depth investigations and analysis. He sought the truth, not its consequences. Two theoretical physicists at the University of Turin, both experienced at science communication, have crafted this fast-paced narrative. They steer us through Gamow's every move, introducing the many atomic and nuclear physicists he encountered and the succession of intellectual puzzles that attracted his fleeting attention. The vibrancy and companionship of continental physics in the interwar period is vividly captured.

The authors draw heavily on Gamow's autobiography *My World Line* from which we learn that Gamow, a child of the Russian Empire, was born in Odesa; the teenager experienced both 1917 Revolutions; the autodidact studied mathematical textbooks while the Red and White armies fought nearby; the studious undergraduate enrolled at St. Petersburg university thanks to the family silver. Aleksandr Friedman's lectures on General Relativity consolidated Gamow's interest in theoretical physics. In his fruitful early career, Gamow networked with brilliant physicists in Göttingen, Copenhagen, and Cambridge. When he applied quantum mechanics to nuclear physics, he explained radioactive alpha decay as quantum-mechanical tunnelling, an impressive result for a newcomer. That led him to consider the inverse, that protons could tunnel into a nucleus, thus igniting his interest in nucleosynthesis and the origin of the elements. Gamow pioneered the liquid-drop model of the nucleus, but he left Niels Bohr to pencil in essential refinements and claim the kudos.

Gamow fled Stalin's Russia in 1934. He held a professorship at George Washington University for twenty years. From 1945 his research student, Ralph Alpher, dutifully worked on nucleosynthesis in Lemaître's fireworks universe, leading to the famous αβγ paper of 1948 and Alpher's prediction of a temperature of 5K for the relict radiation.

The biography entertains the reader with its development of the character of the protagonist. However, the authors rely on just a handful of sources, principally the unreliable autobiography in which Gamow indulges in quixotic romancing. Considered as a contribution to science communication, it would have benefitted from critical redrafting by a development editor with experience of trade publishing. — SIMON MITTON.

Other Books Received

Principles of Astrophotonics, by Simon Ellis, Joss Bland-Hawthorn & Sergio Leon-Saval (World Scientific), 2023. Pp. 286, 23·5 × 15·5 cm. Price £40/$48 (paperback; ISBN 978 1 80061 335 5).

Astrophotonics is the application of photonics to astronomical instrumentation. This rapidly developing field is a new approach to instrumentation in which the bulk optics of traditional instruments, such as lenses, mirrors, and diffraction gratings are replaced with devices embedded within waveguides. This is the first book focussed on astrophotonics, written by three experts in the field. Beginning with a sound introduction to the basic principles of astrophotonics, it is intended to communicate the current status, potential, and future possibilities of astrophotonics to the wider astronomical, optics, and photonics communities.

Congratulations

The Editors are delighted to send their congratulations and best wishes to Professor Sir Francis Graham-Smith, FRS, on reaching his 100th birthday on 2023 April 25. He has been a long-time contributor of papers and reviews to this *Magazine* and he remains active academically. The first paper which he submitted to *The Observatory*, entitled 'A search for radiation from Jupiter at 38 mc/s and 81·5 mc/s', appeared in Vol. 75 in 1955. The fifth edition of *Pulsar Astronomy*, which he co-authored, was published in 2022 and is reviewed in the next issue.

Here and There

TO ERR IS HUMAN

Milton Humanson and the Expanding Universe — *Astronomy Now*, 2023 January, Front cover.

A UNIQUE AIRCRAFT

SOFIA was a telescope mounted on a Boeing 474 that was recently retired from service. — *BBC Science Focus*, New Year 2023, No. 386, p. 31.